Movement Control in Clumsy Children: Visuoperceptual Ability and Hemispheric Specialisation in Aimed Reaching

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Except where otherwise indicated this thesis is my own work.

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Abstract

The major aim of the study was to assess visuoperceptual ability in a group of clumsy children and a control group, and examine the relationship between visual perception and reaching performance. Visuoperceptual ability was assessed by examining the children's ability to make visual judgements about the direction of reaching targets. In the same experimental environment as the visuoperceptual task, visuomotor performance was investigated by analysing the early and late stages of aimed reaching under three different viewing conditions (full vision, restricted view of hand, restricted view of hand and target). A second aim of the study was to examine hemispheric specialisation for visual perception and motor control in clumsy children. This was achieved by comparing left and right visual-field performance for the visuoperceptual task (judgement of target direction), and by assessing reaching performance in different left and right target/hand combinations.

The study found that clumsy children performed more poorly than controls in the visuoperceptual task. Analysis of the reaching task showed that the clumsy children were more variable in the initiation of reaching movements, independent of the viewing conditions. However, these group differences in initial error variability were not related to differences in visuoperceptual ability. The clumsy children were also more variable than the controls at the end of the reaching movement with the difference being greatest under restricted viewing conditions. In contrast to movement initiation, the group difference in end-point variability was related to visuoperceptual performance for the full vision condition, but not for restricted viewing conditions. Other results showed that control children performed equally well regardless of hand or target used, however, the clumsy children were less accurate in the predominantly right hemisphere conditions of left hand and left hand/left target.

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Chapter 1

Introduction

Most children possess sufficient motor skill to perform basic living tasks such as eating, writing, dressing and playing. Some, however, are so poorly coordinated that normal daily functioning is compromised. These children are commonly described as "clumsy". The "clumsy child" is characterised by impaired motor performance which interferes with daily activities despite normal intelligence and no obvious neurological deficits (Gubbay, 1975; Hulme, Biggerstaff, Moran and McKinlay, 1982a; Hulme and Lord, 1986). Poor motor skills may also affect other spheres of life such as emotional development and educational achievement (Henderson and Hall, 1982; Laszlo, 1990; Laszlo, Bairstow, Bartrip and Rolfe, 1988; Smyth, 1992; Sovik and Maeland, 1986) and may persist into young adulthood (Hellgren, Gillberg, Gillberg and Enerskog, 1993; Losse, Henderson, Elliman, Hall, Knight and Jongmans, 1991).

Coordination problems are often grouped together with other developmental delays, such as dyslexia, where the cause is not attributable to known neurological abnormalities (American Psychiatric Association, 1994). However, to develop appropriate clinical strategies to assist clumsy children, it is important to understand the determinants of impaired motor control for this group. A process-oriented approach to motor difficulties enables a functional understanding of the underlying causes of poor motor skills in clumsy children to be achieved (Laszlo, 1990; Laszlo and Bairstow, 1985). Information processing models of motor control typically describe four connected components: input, central processing, output and feedback loops (e.g. Laszlo and Bairstow, 1985; Magill, 1989; Marteniuk, 1976; Sage, 1984). By assessing the integrity of underlying processes in clumsy children, it is possible to identify major abilities necessary for adequate performance of perceptual-motor skills, and facilitate diagnosis and treatment of children with coordination problems (Laszlo, 1990; Laszlo and Bairstow, 1985; Laszlo and Sainsbury, 1993).

Processing of visual information is a key factor at a number of stages in the control of simple movements, such as aimed reaching (Jeannerod, 1986). For example, in the input stage, before reaching has commenced, vision is used to judge the distance and direction of the target preparatory to planning and initiation of the movement. The early stage of the movement is initiated on the basis of this information, and is usually regarded as preprogrammed and not yet modified by corrections based on feedback (Jeannerod, 1988; Magill, 1989; Marteniuk, MacKenzie, Jeannerod, Athenes and Dugas, 1987; Sage, 1984). In the later part of the reaching movement, visual information from the target and/or the moving hand, together with kinaesthetic feedback about the arm trajectory, provide a basis for error correction. Thus, vision is important for both input and ongoing corrections based on feedback and a deficiency in visual processing might contribute to motor deficits in clumsy children.

Deficits in both visual and kinaesthetic processing have indeed been documented in samples of clumsy children (Bairstow and Laszlo, 1989; Hulme et al., 1982a; Hulme, Smart and Moran, 1982b; Hulme, Smart, Moran and McKinlay, 1984; Laszlo, 1990; Laszlo and Bairstow, 1985; Laszlo et al., 1988; Laszlo and Sainsbury, 1993; Lord and Hulme, 1987a and b; Smyth, 1994). The study reported in this thesis focuses primarily on the role of visual information in motor control in these children. The first aim of this study was to confirm the existence of visuoperceptual deficits in clumsy children and identify how these deficits affect the operation of mechanisms underlying visuomotor control of reaching movements.

The second aim, was to investigate whether clumsy children have impairment in right hemisphere processing for visual perception and motor control in aimed reaching movements. Since processing of perceptual information is commonly regarded as a right hemisphere function (Benton, 1985; Bryden, 1982; Lezak, 1983), it is possible that the perceptual deficits observed in clumsy children might arise from impaired right hemisphere functioning. In this case, clumsy children might be expected to show other deficits associated with right hemisphere impairment. In particular, they might be expected to show deficiencies in the nonperceptual components of motor control that are associated with right hemisphere functions, such as initial response programming. The nature of these components are reviewed in Section 1.1.3.

The first section of this chapter briefly summarises the literature pertaining to visual processing and hemispheric specialisation in the control of reaching movements by normal adults and children. The second section addresses information processing issues as they relate directly to clumsy children. Finally, the investigation carried out in the present study is outlined and described.

1.1 Components of Movement Control

1.1.1 Information Processing Models of Movement

A motor skill includes any activity "that has a goal to achieve and that requires voluntary body or limb movement to be properly performed" (Magill 1989, p7). Motor skills can be classified into different categories according to the type of task performed. For example, gross motor skills involve large musculature and may be distinguished from fine motor skills which require the control of the small muscles of the body (Magill, 1989). However, such a task-oriented approach has limited utility. There are elements of motor control common to all types of movement. A process-oriented approach offers the opportunity for a more complete understanding of the difficulties facing the child (Laszlo, 1990; Laszlo and Bairstow, 1985).

Aimed reaching is a type of movement that has frequently been used in studies of movement control. It is highly practised and involves parameters which are easily manipulated. In aimed reaching, the goal of the control system is to produce a movement that transports the finger tip to the target location by the most direct route and in minimum time. Efficient execution of the reach results in smooth acceleration and deceleration with few perturbations.

Information processing models can readily be used to describe the control of reaching movements. The relevant components of a simple information processing model are depicted in Figure 1.1 (adapted from Laszlo and Bairstow, 1985 and Marteniuk, 1976). Performance is likened to a communication system. Information is received from the environment, body position and instructions (input), processed by the central nervous system (perceptual processing, motor planning and programming) and then information is sent to the muscles so that movement can occur (output). Afferent information (sensory feedback) is also sent by the sensory receptors to update the central nervous system (Marteniuk, 1976).

Input includes all stimuli that the subject receives before starting the movement. All the senses, such as vision, hearing, touch and balance, can be used to assess information about the individual and the environment relevant to planning the action (Laszlo and Bairstow, 1985; Marteniuk, 1976). For example, in a reaching task vision is used to judge the position and size of the target before movement is commenced. The individual can also evaluate the posture of the body and limbs prior to beginning an action on the basis of visual information.

Kinaesthesis[1] provides information about the relative positions of body and limbs and the level of tension maintained in the various muscles from tendon, joint and muscle receptors (Hulme and Lord, 1986; Laszlo and Bairstow, 1985; Marteniuk, 1976). Also important at the input stage of a movement is the subject's prior instructions. As well as indicating the tools and strategies to be used, instructions can influence the manner of performance, such as whether the reacher should emphasise speed or adopt a slower, more careful execution of the task.

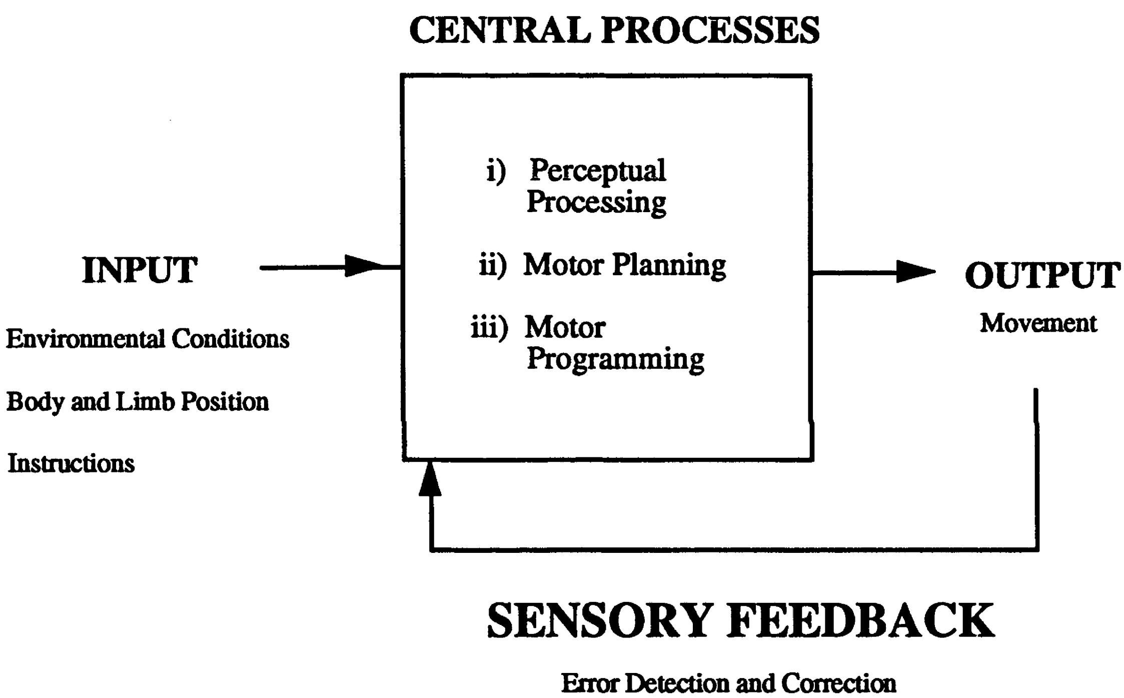


Figure 1.1 Information processing model for skilled movement (adapted from Laszlo and Bairstow, 1985 and Marteniuk, 1976).

[1]The proprioceptive modality is similarly understood to describe all those sensory systems which provide information about location and movement of the body including vestibular, tactile and kinaesthetic information (Reber, 1985). In the text, "proprioception" is used interchangeably with "kinaesthesis", since the contribution of vestibular and tactile information to aimed reaching under laboratory conditions is normally negligible.

Descriptions of the central processes involved in motor control generally distinguish perceptual processing, decision making and programming components (Laszlo and Bairstow, 1985; Magill, 1989; Marteniuk, 1976; Sage, 1984). Perceptual processing involves selecting and recognising incoming sensory stimuli. Visual, kinaesthetic and other perceptual information is encoded, integrated and then stored in memory. Motor planning involves generating a plan of action by evaluating the incoming sensory information in light of memory traces of previous attempts. The goal of the task, based on instructions and personal motivation, also determines the motor plan (Laszlo, 1990). Once the plan of action is made, motor programming initiates the required movement. Motor programming is responsible for sending motor commands to the muscular system to select and activate the relevant muscles required to achieve the chosen goal. Motor programming allows for flexibility and variation in approaches to identical goals so that the same skill can be performed in many ways. In active movement, a corollary discharge is present which allows an immediate comparison between the motor plan and the actual movement (Laszlo and Bairstow, 1985).

The output is the actual muscle response which determines the direction, force and speed of the reaching hand. This can be observed as either a shortening or lengthening of muscle or as a change in the tension of the muscle (Laszlo and Bairstow, 1985; Magill, 1989).

The sensory feedback loop projects information back to the central nervous system for evaluation of the success of the movement. Output is monitored by this feedback loop and enables error detection and correction. When errors are detected, central processes generate an appropriate corrective program. Feedback information is generated by all the sensory channels including kinaesthesis, vision, hearing and touch. Kinaesthetic feedback is always present since any movement automatically returns information about body position and muscle tension for processing by the central nervous system (Laszlo and Bairstow, 1985). The relative contribution of the various sensory channels depends on the task. For example, vision provides important information for determining the ongoing success of an aimed reaching movement but hearing is more important in violin playing (Laszlo and Broderick, 1985).

1.1.2 Mechanisms underlying Visuomotor Control of Reaching Movements

The role of vision in the control of reaching movements has been central to experimental investigations of motor control (Jeannerod, 1986; Blouin, Teasdale, Bard and Fleury, 1993). Models for the control of visually guided reaches have commonly distinguished two phases (Jeannerod, 1988; Magill, 1989; Marteniuk et al., 1987; Sage, 1984). An initial, preprogrammed phase is responsible for bringing the hand into the vicinity of the target and is usually regarded as being executed without relying on perceptual feedback. The closed loop or feedback phase is under kinaesthetic and visual regulation and is responsible for stopping the hand accurately on the target at the end of the movement (Blouin et al., 1993; Marteniuk et al., 1987).

The initial, preprogrammed phase of a goal directed movement comprises perceptual, planning and motor programming processes that are based on information available before starting (Prablanc and Martin, 1992). This initial phase, often described as being under "open-loop control", only utilises perceptual information available at the input stage, such as judgements of target direction and size. Vision of the moving hand makes a negligible contribution in this phase. Support for this contention comes from studies which have shown that withdrawing vision of the hand during the initial phase of the movement has no effect on terminal accuracy (Beaubaton and Hay, 1986; Carlton, 1981). It has also been demonstrated that there is an intrinsic sensorimotor delay, estimated to be about 100 to 150 milliseconds, in the processing of both visual and kinaesthetic information (Carlton, 1981; Elliott, 1993; Jeannerod, 1986; Keele and Posner, 1968; Prablanc and Martin, 1992). This implies that no feedback corrections can occur before this time and that approximately the first 150 milliseconds of aimed reaching are preprogrammed (Blouin et al., 1993; Zelaznik, Hawkins and Kisselburgh, 1983).

It has been generally accepted that the role of visual feedback in aimed reaching is to control spatial accuracy at the end of the movement. Errors resulting from the initial motor program can be corrected by comparing the position of the seen hand with that of the seen target (Jeannerod, 1986; Prablanc, Pelisson and Goodale, 1986). In particular, amplitude rather than direction is most likely to be modified (Bard, Hay and Fleury, 1990). There is generally a speed/accuracy trade-off in visually guided movements, with slower movement times usually representing greater accuracy (Blouin et al., 1993; Fitts, 1954; Marteniuk et al., 1987). This inverse relationship has generally been interpreted as reflecting the additional time necessary to execute corrections based on sensory feedback.

Experimental investigations have tended to emphasise two types of visuomotor control: preprogramming and correction based on a visual feedback loop. However, studies have shown that corrections to the trajectory are still made in the absence of visual information about the position of the moving limb which suggests that kinaesthetic feedback is also utilised (Jeannerod, 1986). Short of interfering directly with the proprioceptive system using methods such as deafferentation or anaesthesia (McCloskey, 1978), the contribution of a kinaesthetic feedback loop to visually guided movements is difficult to assess. However, research suggests that there may be a non-visual feedback mechanism involved which can be successfully manipulated in the experimental environment by changing the visually defined target. It has been shown that pointing movements made without vision of the limb are more accurate when the target is visible throughout the movement than when it disappears shortly after movement initiation (Prablanc, Pelisson and Goodale, 1986). This suggests that when the target is visible, there is a corrective process which compares the kinaesthetically signalled progress of the limb with the visually defined target location.

It is possible this same corrective process is also utilised when the target is not visible throughout the movement. In this case, the visual representation of the target would be based upon the memory of the previously seen target position, and the decline in reaching accuracy might simply be attributed to decay in the representation over time. However, a suggestion that this is a special correction mechanism based on the continuous view of the target is provided by evidence that shows corrections are made to the unseen moving hand even when the subject is unaware of shifts in target position (Prablanc and Martin, 1992). If the target is shifted during the maximum velocity of a visual saccade, the subject does not consciously perceive the change. Studies have shown that if target distance or direction is changed under these conditions, subjects nevertheless make corrections that are incorporated smoothly into the trajectory (Goodale, Pelisson and Prablanc, 1986; Pelisson, Prablanc, Goodale and Jeannerod, 1986; Prablanc and Martin, 1992). Reaction times to the target perturbations are approximately 150 ms and corrections appear to be made continuously. Taken together, this work suggests the existence of a rapid corrective mechanism based on continuous comparisons between the visually observed target and the kineasthetically located limb. This mechanism will be termed a <u>visuo-kinaesthetic</u> loop. This loop is expected to be disrupted if the visual stimulus were not continuously visible throughout the movement.

In a visually guided reaching movement, control mechanisms such as visual feedback, visuokinaesthetic feedback and preprogramming are usually smoothly integrated resulting in a unimodal speed time curve (Mathew and Cook, 1990; van der Meulen, Gooskens, Denier van der Gon, Gielen and Wilhelm, 1990). However, it is possible to identify one or other process as dominant depending on the environmental conditions. For example, in conditions where precision requirements are high, studies have shown that the deceleration phase increases allowing more time for visual feedback processes to dominate (Marteniuk et al., 1987). However, in uncertain conditions where the availability of visual information is unpredictable, reliance on visual feedback is reduced and subjects are more likely to preprogram their reaches (Jakobson and Goodale, 1991; Zelaznik et el., 1983).

Three experimental conditions have frequently been used in studies of visually guided reaching to investigate the mechanisms described above. When Full Vision of both the target and hand is available the reach is normally smooth, rapid and accurate. All control mechanisms described above are available for utilisation. End-point errors are rare when visual feedback is available: constant error (the mean of end position relative to target position) is virtually zero and variable error (the scatter of pointing positions) is low. The high relative accuracy of the full vision condition can be attributed to the precision of the visual feedback loop (Jeannerod, 1986).

In conditions where there is Restricted View of the Hand, utilisation of the visual feedback loop is precluded. Yet, other mechanisms such as preprogramming and visuokinaesthetic feedback are available for motor control. Reaches made under these conditions show similar spatiotemporal movement characteristics to movements made when full vision of the hand is allowed. That is, no difference between the Full Vision and Restricted View of the Hand conditions is observed for parameters such as movement duration, and velocity and acceleration profiles (Prablanc and Martin 1992). While reaching is observed to be significantly less accurate in the Restricted View of the Hand condition (Jeannerod, 1986; Prablanc and Martin, 1992), corrections made on the basis of non-visual information about the moving hand have been observed to compensate for 90% of target changes (Prablanc and Martin, 1992). Thus, it appears that in conditions where view of the hand is restricted throughout the movement, visuokinaesthetic information is utilised for ongoing corrections to the motor program in much the same way that visual feedback is utilised in Full Vision conditions.

If the target is extinguished prior to movement, that is, there is Restricted View of Hand and Target, the opportunity to use visually based corrective mechanisms such as visual and visuokinaesthetic feedback loops is reduced. Reaches made under these conditions show significantly greater errors and, as Fitts' law predicts, the spatiotemporal characteristics change and the movement becomes significantly faster (Prablanc et al., 1986). Poor initial judgement of target position and uncorrected programming and execution errors are likely to be the main source of error in these conditions (Prablanc et al., 1986). However, it is also possible that even without a visible target, subjects may attempt to utilise kinaesthetic or visuokinaesthetic feedback processes by remembering the target position (Blouin et al., 1993). A further source of error may then arise from poor memory for target location.

1.1.3 Hemispheric Specialisation in Visual Perception and Motor Control

Traditionally, the left hemisphere has been seen as the dominant hemisphere for controlling skilled, purposive movement (Bryden, 1982; Williams, Werner and Purgavie, 1986). The majority of the population demonstrate right preferences for the hand, foot and eye, and this has been considered to be a reflection of left hemisphere dominance of motor control. However, processing of visual information is also important for skilled movement and this has traditionally been seen as a right hemisphere function (Benton, 1985; Bryden, 1982; Joseph, 1988; Lezak, 1983). An analysis of the various components in the information processing model for motor control suggests that there may be differences in the hemispheric control of the main functions such as perceptual processing and feedback control.

One simple perceptual task central to the control of reaching movements is an appreciation of line direction, in particular, direction relative to the starting point of the hand. A number of experimental and clinical studies have produced consistent evidence of right hemispheric contribution to judgement of direction. These studies have investigated appreciation of the directional orientation of lines presented as either tactile or visual stimuli. Results indicate that perception of direction is mediated by the right hemisphere in right-handed subjects (Benton, Varney and Hamsher, 1978; Benton, 1985; Bryden, 1982; Fontenot and Benton, 1972). As long as the line slant task employs angles that are not easily coded verbally it seems to provide a fairly robust left-field superiority (Bryden, 1982). To the extent that the visual perception of target direction relative to the hand is a fundamental component in programming a reach, this finding seems to implicate the right hemisphere in motor processing.

Aiming movements have been used to investigate in more detail the relationship between hand differences in performance and cerebral specialisation of function. It has generally been observed that in both aimed movements and tapping, the speed and accuracy of the dominant hand is superior (Flowers, 1975; Haaland and Harrington, 1989a; Haaland, Harrington and Yeo, 1987; Roy and Elliott, 1986; Todor and Cisneros, 1985; Todor and Doane, 1978; Todor and Smiley, 1985). Preferred-hand superiority tended to become more pronounced when the accuracy demands of rapid movements were increased and the movement time was greater (Flowers, 1975; Roy and Elliott, 1986; Todor and Cisneros, 1985; Todor and Doane, 1978). This led researchers to propose that the left hemisphere is dominant for making corrections based on visual feedback (Todor and Smiley, 1985). In support of this, Todor and Cisneros (1985) found that slower left-hand movement times were attributable primarily to the terminal homing-in phase, especially as target size decreased. Annett, Annett, Hudson and Turner (1979) obtained similar results for peg board placement. Overall, these studies suggest that the superiority of the right hand is primarily attributable to performance in the later phase of the movement where utilisation of visual feedback is generally thought to be most important.

Movements where utilisation of feedback processes is limited do not always produce significant differences favouring the dominant hand. Todor and Doane (1978) found the performance of the left hand increased when the reaching tasks were modified to reduce the demand for visual feedback and suggested that the right hemisphere may be involved in preprogrammed movement control. In some cases, performance with the left hand and/or left hemi-space has been superior to right-sided equivalents. Guiard, Diaz and Beaubaton (1983) investigated hand differences in rapid (ballistic) aimed movements with the active hand hidden, and found a superior performance when the right hemisphere was engaged. Right-handers performed rapid aimed movements with a smaller constant error when using the left hand or when the target was presented on the left side, and accuracy was greatest for the left hand/left field combination. In another study, thumb positioning in blindfolded subjects was also found to be more accurate and consistent with the left hand (Roy and MacKenzie, 1978), although it is possible that this effect reflected differences in kinaesthetic processing rather than a differential ability to reproduce movements without visual feedback. Nevertheless, together these three studies suggest that when utilisation of visual feedback is precluded, a superior advantage is observed for right hemisphere processing.

Studies investigating reaction time in movement preparation provide further evidence for right hemisphere dominance in preprogramming a motor response. Reaction times have been found to be quicker for stimuli projected from the left hemi-space (Heilman and van den Abell, 1979) and Haaland and Harrington (1989a) found shorter reaction times for the left arm of normal subjects. These results are consistent with more efficient programming of the initial motor response by the right hemisphere. This could be due to the right hemispheres role in visuospatial processing or alternatively it might reflect a superior performance for attention and response preparation. Further support for a preprogramming advantage for the right hemisphere was seen in a study of fencers which showed that the reaction times of the left hand in left-handed fencers were significantly faster for a divided attention condition (Bisiacchi, Ripoli, Stein, Simonet and Azemar, 1985).

Clinical studies with brain damaged clients also point to the importance of the right hemisphere in the control of movement. Geschwind and Damasio (1985) observed that many apraxic patients with lesions of the left hemisphere demonstrate impaired limb and buccofacial movements, yet performance of axial movements remain intact. They suggested that the right hemisphere may be better at controlling axial and other relatively automised movements, with the left hemisphere more specialised for the fine movements of the hand and face. Lesions of the right posterior parietal cortex have been found to produce disorders of behaviour in the immediate surrounding space (Jeannerod, 1986). Typically, patients demonstrate misreaching for the hand and/or the hemi-space contralateral to the lesion, even though spatial discrimination based on sensory cues alone may be normal (Vighetto, 1980 in Jeannerod, 1986). Haaland and Harrington (1989a) found that right hemisphere stroke patients were less accurate than control groups when reaching towards a narrow target with their right hand and that they had slower reaction times in their contralateral arm relative to controls. Although Haaland and Harrington (1989b) failed to replicate their results, in general, clinical studies provide support for the role of the right hemisphere in movement control.

Overall, the results suggest that the right hemisphere contributes to the control of movements which are largely dependent on perceptual input or spatial orientation, and is dominant for programming of the initial motor response. On the other hand, the left hemisphere is dominant for movements that require sequential fine motor adjustments and/or rely on processing of visual feedback for movement control. The existence of conflicting evidence on this issue can probably be attributed to the special difficulties of investigating asymmetries in motor performance. Problems that may produce confounding evidence in studies of cerebral lateralisation in motor control include differential practice effects for the dominant hand (Haaland and Harrington, 1989a), incomplete contralateral representation for hemi-space and limb musculature (Brinkman and Kuypers, 1972) and variations in the size and within-hemispheric localisation of lesions for brain damaged subjects (Bryden, 1982).

1.1.4 Developmental Changes in Movement Control

1.1.4.1 Preprogrammed and Feedback Processes in Development

Studies show that aimed reaching is a skill acquired early in life and that infants can make use of both feedback and preprogrammed processes for control of movement (Mathew and Cook, 1990). However, there is evidence that changes occur in the relative dominance of various control processes as the child develops. Spatial accuracy, reaction time and movement time have all been observed to vary as a function of age in studies of aimed reaching in children. Contrary to expectations, changes in the parameters of reaching movements do not simply show a steady increase in proficiency in reaching. Rather, it appears that during development there is a change in strategy; from reliance on predominantly preprogrammed movements, to predominantly feedback control and, finally to smooth integration of feedback and preprogrammed processes (Zanone, 1990).

Younger children, between the ages of four to six, appear to execute movements which are largely preprogrammed and make little use of feedback mechanisms (Hay, 1978, 1979). Directional accuracy at this age, which seems to load mainly on the initial stage of the response, is relatively well developed (Bard et al., 1990). Thus, when visual feedback from the hand is not available, they show close-to-adult levels of accuracy in movements (Hay, 1978). Nevertheless a relative inefficiency in programming at this age is demonstrated by longer reaction times (Bairstow, 1989; Sugden, Waters and Harper, 1986) and greater susceptibility to task difficulty (Bairstow, 1989).

In contrast to both younger children and adults, seven and eight year olds appear to rely on visual or visuokinaesthetic feedback control and make ongoing corrections for the greatest part of the movement (Hay, 1978, 1979). Children in this age group take more time to complete a visually guided movement than do older children (Bard et al., 1990) and the age differences in movement duration appear mainly in the homing time (Schellekens, Kalverboer and Scholten, 1984; Kerr, 1975). The lack of efficiency in using this mode of control is reflected in increased errors (Brown, Sepher, Ettlinger and Skreczek, 1986; Hay, 1978, 1979), particularly in conditions when only visuokinaesthetic feedback is available (Bard et al., 1990; Fayt, Minet and Schepens, 1993). The ability to accurately process kinaesthetic information develops rapidly in the six to seven year old (Laszlo, 1990) and thus, utilisation of proprioceptive information is a newly acquired skill for the seven to eight year old child (Elliott, Connolly and Doyle, 1988; von Hofsten and Rosblad, 1988). Fayt et al. (1993) found that learning with vision of the limb improved accuracy in non-visually guided actions for eight year olds only, and suggested that visual feedback is crucial for learning and improving accuracy at this age because of difficulties in using and integrating kinaesthetic information.

Between the ages of nine and eleven, an improvement in style and efficiency is observed and a more adult-like reach is achieved. More appropriate use of open and closed loop mechanisms are observed (Sugden et al., 1986; Schellekens et al., 1984) and the reach starts to display a smooth, integrated unimodal velocity profile. The child is also better able to cope with tasks of increased difficulty such as intercepting a quickly moving target (Bairstow, 1989). Older children (aged 11 to 12 years) demonstrate an increased ability to integrate sensory information (Chicoine, Lassonde and Proteau, 1992). The overall improvement in movement performance appears to reflect both a greater ability to control the ongoing movement via feedback, particularly braking and distance corrections (Bairstow, 1989; Bard et al., 1990) and more sophisticated preprogramming strategies (McCracken, 1983; Sugden, 1980).

Thus, experimental evidence suggests that simple preprogrammed control is relatively well developed in children by the age of five or six. With the emergence of greater kinaesthetic abilities the child starts to rely more on feedback information and efficient use of feedback processes develops over the next few years. Concurrently, information processing capacities also improve and allow for the development of more complex programming abilities. By the age of ten or eleven the child starts to demonstrate integrated and efficient use of preprogrammed, visuokinaesthetic feedback and visual feedback mechanisms.

1.1.4.2 Hemispheric Specialisation in Development

Studies investigating motor control consistently demonstrate a right hand bias in the majority of children from the age of two or three years with little evidence for any developmental change other than increased consistency (Annett, 1970; Bryden and Saxby, 1986; Kinsbourne, 1989). For children between the ages of eight and twelve, the preferred hand is faster (Carlier, Dumont, Beau and Michel, 1993) and less variable in performance (Brown, Schumacher, Rohlmann, Ettlinger, Schmidt and Skreczek, 1989; Carlier et al., 1993 ; von Hofsten and Rosblad, 1988). This is the case even when visual information from the target and hand is removed (von Hofsten and Rosblad, 1988). Nevertheless, Brown et al. (1989) found that children using their non-preferred hand had significantly shorter reaction times, which is consistent with adult studies that point to more efficient programming of initial motor responses by the right hemisphere.

Less is known about the development of hemispheric specialisation for non-verbal activities which are usually regarded as right hemisphere functions. It appears that right hemisphere lateralisation of simple perceptual processes such as judging spatial coordinates and haptic perception is relatively well developed by the age of five (e.g. Bryden and Saxby, 1986; Kinsbourne, 1989; Koenig, Reiss and Kosslyn, 1990; Rourke, Bakker, Fisk and Strang, 1983). On the other hand, lateralisation of more complex spatial processing may only emerge later, as the brain matures and the child adopts new strategies. For example, younger children (two to six years) appear to have difficulty crossing the midline, and in a line bisection task err to the left with the left hand and to the right with the right hand (Bradshaw, Spataro, Harris, Nettleton and Bradshaw, 1988; Roeltgen and Roeltgen, 1989). The adult lateralisation pattern of erring to the left with both hands was not observed until seven or eight years. Because symmetrical neglect is also observed in adults with lesions of the corpus callosum, this has been interpreted as being related to the lack of myelanation of the corpus callosum in young children (Bradshaw et al., 1988; Roeltgen and Roeltgen, 1989). For complex visuospatial tasks, sensory motor processing may only become more lateralised as the corpus callosum matures and reliance on contralateral pathways emerges (Bradshaw et al., 1988; Kinsbourne, 1989).

In summary, for children over the age of seven we observe the same hemispheric specialisation for processes in simple motor control as seen in adults. Thus, the dominant hand is quicker and more accurate, but programming of movement initiation may be more efficient when mediated by the right hemisphere. Like adults, children rely more exclusively on the right hemisphere for processing of nonverbal information although it appears that a left lateral advantage only gradually emerges for complex visuospatial tasks. This does not mean however, that children display the same adult patterns of lateralisation in task performance. As many experiments assessing lateralisation have demonstrated, the particular strategy adopted in performing the task (e.g. verbal encoding of nonsense symbols) can greatly influence lateralisation effects. For children under the age of ten or eleven, variations in selection of processing strategy could well yield differences from the adult motor performance patterns.

1.2 Deficits in Clumsy Children

1.2.1 What is a Clumsy Child?

The clumsy child typically presents with difficulties in a wide range of motor skills. These include frequently falling and bumping into things, messy eating, poor dressing, difficulties with drawing and illegible handwriting. Usually, both fine and gross motor skills are affected (Smyth, 1992). The child has usually come to the attention of teachers or parents when seven or eight years because of inferior performance relative to school peers (Laszlo and Sainsbury, 1993; Laszlo et al., 1988). Approximately 5-10 per cent of primary school children are thought to have coordination skills significantly below that expected for their age (Gubbay, 1975; Johnston, Short and Crawford, 1987; Laszlo, 1990; Sovik and Maeland, 1986) and the clumsy child is three to four times more likely to be male (Gordon and McKinlay, 1980; Gubbay, 1978; Laszlo et al., 1988; Sovik and Maeland, 1986).

Because perceptual-motor skills are needed for educational and living tasks, the child may also have learning difficulties, behaviour problems and delayed emotional and social development (Laszlo, 1990; Laszlo and Sainsbury, 1993; Laszlo et al., 1988; Melamed and Rugle, 1989; Roussounis, Gaussen and Stratton, 1987; Smyth, 1992; Sovik and Maeland, 1986).

Attention was drawn to the disorder by Walton and colleagues (Gubbay, Ellis, Walton and Court, 1965; Walton, Ellis and Court, 1962) who described clumsy children as suffering from "developmental apraxia and agnosia". Identified children showed isolated defects of motor planning (praxis) or visuospatial recognition (gnosis) despite a verbal IQ within normal limits and no other signs of neurological disturbance. Since then, researchers have not always agreed on the nature of the definition and have used a variety of sampling procedures in studies. There has been a lack of consensus on the identification of motor problems between classroom teachers, therapists, physical education specialists and motor-skill tests (Keogh, Sugden, Reynard and Calkins, 1979; Sovik and Maeland, 1986). This disagreement is reflected in the many names for the clumsy child including the "physically awkward" or "uncoordinated child", "perceptual-motor dysfunction", "developmental dyspraxia", or "apraxia and agnostic ataxia" (Ayres, 1972; Cermak, 1985; Laszlo, 1990; Laszlo and Sainsbury, 1993; Laszlo et al., 1988; Walton et al., 1962).

In spite of this disagreement, clinicians and researchers have tended to agree that a specific childhood syndrome exists in which clumsiness, or exceptionally poor motor coordination, is the dominant or only characteristic. Clumsiness or coordination problems are often grouped together with other circumscribed developmental delays, such as dyslexia, where the cause cannot be attributed to any other identified pathology. The identification of these developmental disorders is made on the basis of a particular ability being at a standard well below that expected by the child's intelligence level (American Psychiatric Association, 1994).

This diagnostic criterion assumes implicitly that IQ and the specific abilities concerned are related. The various developmental syndromes identify groups of children who are an exception to the rule: they have a specific developmental problem despite normal intelligence. Researchers investigating the causes of clumsiness have hypothesised that a bright child who does not excel at motor skills, may have a specific structural dysfunction. However, while skills such as reading ability are usually related to intelligence (Stevenson and Fredman, 1990), there is only a moderate association between motor skill and IQ (Brenner and Gillman, 1966). The IQ/performance discrepancy may therefore be a poor basis for diagnosis. Nevertheless, many children identified as clumsy on this basis have been found to have some minor neurological abnormalities (Gubbay, 1978) and/or histories of birth trauma and significant medical events (Gubbay, 1975; Gubbay et al., 1965; Henderson and Hall, 1982; Johnston et al., 1987; Walton et al., 1962). This tends to validate the criterion and suggests that impaired processing mechanisms may be associated with structural deficits in the clumsy child.

Many clumsy children, however, do not exhibit explicit neurological abnormalities or significant perinatal events and it is possible that the population of clumsy children may include children who fall at the extreme end of the natural variation of motor ability. A history of clumsiness in family relatives of clumsy children has been observed (Gubbay, 1978; Johnston et al., 1987). Below average motor skill may be part of the natural distribution of individual differences as found with height, weight, and artistic or singing ability. It is possible that natural variation may result in a child with normal intelligence inheriting poor abilities for one or all of the underlying processes required in skilled movement. That is not to say that such variations have no structural cause, and even clumsiness which represents extremes of natural variation may have functional implications which can be identified using an information processing framework.

Identification of causes of motor incoordination are further complicated by emotional and environmental confounds. Factors such as poor motivation and lack of opportunity and experience can influence motor skills. A child could perform poorly because of lack of opportunity in the home and school environment, just as relatively untalented children might perform well because they are highly competitive and have been attending regular gym, swimming, tennis lessons etc. from a young age. Nevertheless, at the clinical level a variety of abilities are assessed, and children with fundamental motor problems will be identified by their relative difficulties in learning and performing novel and less practised motor tasks.

The American Psychiatric Association has clearly distinguished the coordination disorder from other related development disorders such as hyperactivity and learning disabilities. According to DSMIV (American Psychiatric Association, 1994), the disorder is manifested by marked delays in achieving motor milestones (walking, crawling, sitting), dropping things, poor performance in sports and/or poor handwriting. An additional criterion is that coordination is so poor that it interferes with academic achievement or activities of daily living. Children who are clumsy because of an identifiable neurological disorder or below average intellectual abilities are excluded by definition.

1.2.2 Perceptual Deficits in Clumsy Children

Adequate perception is important for skilled movement and research has investigated the role of both visual and kinaesthetic perception in clumsy children. Vision is necessary for the judgement of distance and spatial relationships and kinaesthesis provides body movement and limb position information. These perceptual modalities are important at both the input stage for initial programming of the movement and for feedback processing in movement correction. Cross-modal communication between these perceptual modalities is also important for movement control (Hulme et al., 1982a).

In a series of studies Hulme and colleagues reported that clumsiness in children was associated with substantial impairments in processing of visuospatial information. They found that clumsy children have a reduced ability to make visual discriminations for line length and slope, circle area, spatial position and triangle size (Lord and Hulme, 1987a; Lord and Hulme, 1988a). They are also less able to match line lengths in the visual modality (Hulme et al., 1982a; Lord and Hulme, 1987a). These results were not dependant on visual memory, visual acuity or abnormal eye movements (Hulme et al., 1982b; Lord and Hulme, 1987a).

The relationship of kinaesthesis to motor control has also been addressed in a number of studies. In a large clinical study, neurological examination found that 40% of poorly coordinated children had abnormal proprioception (Johnston et al., 1987). Experimental work by Laszlo and colleagues (Bairstow and Laszlo, 1989; Laszlo, 1990; Laszlo and Bairstow, 1985; Laszlo et al., 1988) has found that poorly coordinated children performed significantly below their age level in kinaesthetic acuity (discrimination between two heights) and kinaesthetic perception and memory (the ability to return a shape to its correct position) and benefited from specific kinaesthetic training. Replications of their work obtained support for differences in kinaesthetic acuity (Hoare and Larkin, 1991; Lord and Hulme, 1987b). Other studies have found that clumsy children were inferior when matching line lengths in the kinaesthetic modality (Hoare and Larkin, 1991; Hulme et al., 1982a) and were also less able in linear position and weight discrimination (Hoare and Larkin, 1991). Additional support for the presence of kinaesthetic processing deficits in clumsy children was provided by Smyth (1994; Smyth and

Glencross, 1986) who found that the reaction times of clumsy children to kinaesthetic stimuli were longer than those of control information.

The ability to integrate information from different perceptual modalities is an important skill necessary for movement control mechanisms such as visuokinaesthetic feedback loops. While there have been a number of investigations into visual and kinaesthetic abilities in clumsy children, there has been a paucity of investigations into cross-modal ability in clumsy children. Hulme and colleagues (1982a) investigated the ability of clumsy and control children to match line lengths in visual, kinaesthetic and cross-modal conditions and found that clumsy children made significantly more errors than controls in both the visual-kinaesthetic and kinaesthetic-visual conditions. However, a replication of these tasks with a much larger group produced less consistent results, although a trend was observed for clumsy children to be inferior in cross-modal matching with presentation in the visual mode (Hoare and Larkin, 1991).

Overall, the experimental evidence implies that a large proportion of clumsy children may have visuoperceptual problems and/or kinaesthetic processing deficiencies. Difficulties may also occur in the integration of kinaesthetic and visual information in cross-modal conditions. Nevertheless, while the demonstration of perceptual problems in clumsy children is promising, this does not indicate whether perceptual problems simply coexist with motor problems in clumsy children, or whether perceptual difficulties contribute directly to poor motor control. Further evidence is required before it can be concluded that impaired visual and/or kinaesthetic perception are the major processing deficits causing motor incoordination in clumsy children.

1.2.3 The Effect of Visuoperceptual Deficits on Motor Control

Although Hulme et al. (1982a) observed visuoperceptual, kinaesthetic and cross-modal deficits in clumsy children, only visuoperceptual ability was significantly correlated with general motor ability. On the basis of this, they hypothesised that poor processing of visual information played an important role in clumsiness. However, the perceptual requirements differ for underlying mechanisms of movement control. It may be that impaired visual processing results in inaccurate visual judgements at the input stage affecting the integrity of preprogrammed motor control. However, visuoperceptual deficits could also affect the processing of visual information returning via feedback loops.

Prior to initiating an aimed reaching movement, visual input provides information about the size, distance and direction of a static target. If processing of this information is imperfect, initial programming will be made on the basis of inaccurate input and errors would be expected early in the movement. For example, relatively large errors in initial angle of direction might be observed. This might be constant or variable over trials, depending on the nature of the visual problem. If opportunities for ongoing correction via visual or visuokinaesthetic loops were limited by the viewing conditions, or there was a deficit in error correction mechanisms, these errors would continue to be manifested late in the movement, for example, as increased end-point error.

For visual feedback control, accurate vision of the moving limb relative to the target is required. The ability to use visual feedback can reduce demands on the perceptual system since only relative, rather than absolute egocentric perception is required. Furthermore, information on the success of the movement is continuously available and the subject can make a number of corrections to finally achieve accuracy. Thus, even if visual perception is impaired in clumsy children, visual feedback mechanisms may enable satisfactory completion of a movement, if there are no time constraints. However, reliance on visual feedback might result in more inefficient and variable movement patterns towards the end of the movement (van der Meulen, van der Gon, Gielen, Gooskens and Willemse, 1991a).

Visuoperceptual deficits might also affect visuokinaesthetic feedback control where the opportunity to utilise visual feedback mechanisms has been limited, for example, reaching for a target without vision of the moving hand. In order to make ongoing corrections in this situation, it is essential to establish an internal target representation and have cross-modal communication between the visual and kinaesthetic modalities (Blouin et al., 1993; Prablanc et al., 1986). Throughout the movement, impaired visuoperceptual judgements will affect the quality of the internal target representation and reduce the accuracy of cross-modal integration. Moreover, because error adjustments require comparisons between visual and kinaesthetic modalities, they do not provide direct information about the success of ongoing corrections and therefore limit opportunities for achieving final accuracy. Thus, in conditions where visuokinaesthetic mechanisms predominate, we would expect to see an increase in both absolute and variable end-point errors in subjects with visuoperceptual deficits.

In summary, the observed visuoperceptual deficits in clumsy children could affect both preprogramming and feedback mechanisms. In normal reaching conditions, if preprogrammed control were primarily affected the clumsy child would be expected to make greater initial errors and rely more heavily on visual feedback processing for correction. On the other hand, if visuoperceptual deficits affect visual feedback mechanisms, the child might nevertheless utilise these mechanisms, albeit inefficiently, to correct observed errors if time permits. Visuoperceptual deficits might also affect visuokinaesthetic feedback control by reducing the accuracy of cross-modal integration. Thus, in conditions where utilisation of visual feedback has been prevented, visuoperceptual deficits may also impair visuokinaesthetic feedback control resulting in greater end-point errors.

1.2.4 Preprogramming and Feedback Control in Clumsy Children.

Hulme et al. (1982a) and Lord and Hulme (1988a) have both shown that deficiencies in visuoperceptual judgement are correlated with simple motor skills. However, as mentioned previously, these correlations do not establish a causal relationship between visuoperceptual problems and motor dysfunction in children. Furthermore, they do not distinguish between visuoperceptual deficits related to preprogramming and feedback control mechanisms.

One way to investigate differences in visual feedback mechanisms is to use tracking tasks which, initially, require continuous responses to a moving target. Thus, these movements are typically guided by visual feedback (Zanone, 1990). Clumsy children have been found to perform less well in visually guided tracking tasks (Bairstow and Laszlo, 1989; Lord and Hulme, 1988b; van der Meulen, van der Gon, Gielen , Gooskens and Willemse 1991b): movement path was variable, less time was spent on target and they found it difficult to maintain a constant velocity. These difficulties with tracking tasks suggest that clumsy children experience significant problems in processing visual feedback information.

If visual feedback mechanisms are impaired in clumsy children, then the relative difference in capabilities between clumsy children and controls could be expected to disappear when visual information from the moving hand is unavailable. However, several studies have shown that clumsy and control children are equally affected by the removal of visual feedback. The performance of clumsy children without vision of the hand in tracking target signals (Van der Meulen et al., 1991b), performing a complex movement (Smyth, 1991) and in the ability to draw a triangle (Lord and Hulme 1988a) all showed that clumsy and control groups were equally impaired by absence of vision of the moving hand. That is, control children maintain their relative advantage when the availability of visual feedback is reduced. This implies that differences do not reflect deficiencies in visual feedback but may be attributed to utilisation of visuokinaesthetic feedback, or to earlier processes such as preprogrammed control.

Several studies have analysed the early and late stages of performance in aimed movements with visual information continuously available, to provide additional information on the integrity of preprogrammed control in clumsy children (Forsstrom and von Hofsten, 1982; Schellekens, Scholten and Kalverboer, 1983). The early stage of the movement was presumed to be preprogrammed with the later part of the movement predominantly feedback guided. These studies found that children with motor difficulties performed less well in visually guided movements than control children, with greater variation in performance, more errors and an overall longer response time. Both Forsstrom and von Hofsten (1982) and Schellekens et al. (1983) also found that these children made more movement units per reach and had significantly shorter initial movement units. From these results, Schellekens et al. (1983) concluded that motor impaired children have more difficulties with the initial, preprogrammed phase of the movement. This leads them to spend more time in the execution of the last (corrective) phase of the movement in order to overcome initial problems.

Further evidence establishing preprogramming deficits in clumsy children comes from van der Meulen and colleagues (1991a). They investigated preprogramming and feedback control mechanisms in goal directed movements by manipulating vision of the moving hand as well as by examining the early and late stages of the movements. They confirmed that clumsy and control children were equally affected by removing sight of the hand moving towards the target. In addition, clumsy children showed larger distance variability during the acceleration phase irrespective of the condition. Their results add weight to the hypothesis that impairments in motor control by clumsy children can be attributed to deficits in preprogramming.

Since clumsy children have shown greater errors in the early stages of aimed movements, and also remain disadvantaged when visual information from the hand is removed, it appears that impaired performance is simply a consequence of impairment in control processes prior to movement initiation. However, such a conclusion would be premature. While the evidence implicating impaired visual feedback processing in clumsy children has been weak, it is still possible that clumsy children may also be impaired in this area. Such deficits would not necessarily lead to greater errors since clumsy children might take their inefficiency into account when planning and programming their movements. That is, by compensating for deficiencies, clumsy children may be as successful as normal children in utilising visual feedback to reduce the relative amount of errors. For example, Forsstrom and von Hofsten (1982) observed that children with motor impairments compensated for their problems by aiming further ahead when reaching for a moving target. Other studies have found that clumsy children also had greater movement times (Bairstow and Laszlo, 1989; van der Meulen et al., 1991b; Smyth, 1991), suggesting that clumsy children might take more time in movement execution, to allow for the use of visual feedback mechanisms to overcome inaccuracies.

In summary, a number of experimental studies have demonstrated an impaired performance by clumsy children at the beginning of the movement which suggests that they are deficient in preprogramming mechanisms. However, it is not clear whether impaired preprogramming in clumsy children is a consequence of errors in processing of visual input or inefficient planning and motor programming. While there is some suggestion that planning and motor programming may be impaired (Smyth, 1991; van Dellen and Geuze, 1988), the influence of visuoperceptual deficits in initial movement control is still open to question.

Furthermore, the relationship between visuoperceptual deficits and visual feedback control also remains unclear. Evidence investigating the integrity of visual feedback mechanisms in clumsy children has been inconclusive. However, it is possible that clumsy children are compensating for deficiencies in visual feedback mechanisms and thus there may be a reduction in measurable effects between groups. In this case, a relationship between visuoperceptual deficits and impaired visual feedback processing in clumsy children may only be identified when alternative experimental paradigms are utilised.

1.2.5 Hemispheric Specialisation in Clumsy Children

Investigation of the lateralisation of perception and movement in clumsy children could provide further information about the association between perceptual and motor processes and determinants of observed deficits. However, very few studies have investigated this question. Williams, Keough, Fisher, Seymour and Tanner, (1980) found that children with delays in motor development exhibited unusual hemispheric specialisation for visual and haptic processing, which were opposite to those typically expected in children or adults. Right-handed motorically delayed children exhibited an inferior right hemisphere performance for correct responses to dichaptic material and for speed of response to visual material (letters and shapes), yet they showed right hemispheric superiority for correct responses to visual material. These results provide some evidence of impaired processing of right hemisphere functions in poorly coordinated children and suggest that there may be competition between hemispheres for functions normally considered to be right hemisphere dominant.

Many studies of clumsy children which have measured IQ (to ensure they meet the criterion of normal intelligence) have found that clumsy children who are normal on verbal tasks nevertheless score significantly below normal controls in the shortened form of the WISC-R Performance scale (Gubbay, 1978; Hulme et al., 1982 a and b; Lord and Hulme, 1987 a and b; Walton et al., 1962). The sub-tests in the shortened form of the Performance scale (Block design and Object Assembly) are generally regarded as relatively pure measures of visuospatial organisational and constructional ability (Lezak, 1983). It is also believed to be clinically useful to hypothesise that there are signs of right hemisphere dysfunction when Performance IQ is lower than Verbal IQ (Joseph, 1988; Warrington, James and Maciejewski, 1986; Wilkening, 1989). Thus, the frequently reported V>P discrepancy provides further evidence of visual-spatial deficits in clumsy children and it is possible that these discrepancies may also reflect right hemispheric deficits.

Together, these two studies suggest that poorly coordinated children may have inferior right hemisphere capabilities and/or unusual cerebral lateralisation for processing of visuoperceptual information. However, evidence that relates directly to movement control lateralisation and coordination abilities is still required. An investigation of the laterality profiles of clumsy children (Armitage and Larkin, 1993) found that performance with the left leg was significantly inferior to that of the right for hopping and balance tasks. A greater proportion of clumsy children also had crossed dominance (incongruent preference between hand, foot, eye and ear). The observation of superior right hemisphere processing of sensory information in highly coordinated young adults (athletes), further supports the contention that coordination abilities and/or disabilities may be related to right hemispheric specialisation (Rossi and Zani, 1986).

Although these studies suggest abnormal lateralisation of perception and movement control may occur in clumsy children, they do not establish the locus of the motor problems. For a relationship between visuoperceptual deficits, motor control and impaired right hemisphere processing to be established, further investigations of hemispheric specialisation for underlying perceptual and motor processes in clumsy children are needed. Under appropriate experimental conditions, it is possible that impaired right hemisphere capabilities in clumsy children might be observed as either inferior left visual-field processing for visuospatial material. In addition, greater initial errors for movements, and/or inefficient feedback processing at the end of the movement, might be observed for the left hand and left hemi-space.

1.2.6 Questions Still to be Answered

Researchers have argued that poor performance by clumsy children in a variety of perceptual tasks implies that perceptual dysfunction is responsible for the clumsy child's difficulties in developing adequate motor coordination. However, perceptual skills vary. For example, visuoperceptual skills include the ability to visually judge distances, size, direction and speed, as well as the ability to scan accurately and organise visual information into meaningful wholes. To understand the cause of impaired visuomotor performance, it is important to assess the specific visuoperceptual processes relevant to the motor skill being investigated. This is required firstly, because certain visuoperceptual abilities are likely to be more or less important depending on the experimental task and secondly, clumsy children may have isolated visuoperceptual deficits rather than a general visuoperceptual disability. A direct relationship between the perceptual and motor tasks under investigation increases the power and validity of the experiment and strengthens conclusions about the underlying causes of clumsiness.

Few studies of clumsy children have assessed visuoperceptual abilities specifically related to the motor skills under investigation. Visual discrimination was investigated in a task directly related to drawing of triangles (Lord and Hulme, 1988a). However, no studies have investigated the visuoperceptual abilities of clumsy children in a task directly related to aimed reaching even though aimed movements have been used in a number of studies to investigate motor control in clumsy children (Forsstrom and von Hofsten, 1982; Schellekens et al., 1983, van der Meulen et al., 1991a). Before any conclusions about clumsy children are made on the basis of studies of aimed reaching, it is important to assess the ability of the clumsy child to make visuoperceptual judgements in tasks directly relevant to these actions.

Once deficits in visual abilities relevant to the motor task under investigation are identified, it is also possible to asses the relationship between the specific deficit and the main mechanisms underlying visuomotor control. If there is a causal relationship between visuoperceptual difficulties and clumsiness, the visuoperceptual deficit could be in areas of visual function particularly associated with either preprogrammed, visual or visuokinaesthetic feedback movement control. Thus, it may be, for example, that ability to judge target direction may play an important role in the efficiency of preprogramming but have little influence on corrective feedback mechanisms. Research therefore, not only needs to assess relevant visuoperceptual abilities but must also seek to establish a direct relationship with each of the main mechanisms of visuomotor control.

Investigations into the integrity of particular mechanisms of visuomotor control in clumsy children have yet to understand fully the deficits in preprogramming, visual and visuokinaesthetic feedback control. While studies have consistently shown impairment in the early stages of aimed reaching which suggests they are deficient in preprogrammed mechanisms (Forsstrom and von

Hofsten, 1982; Schellekens et al., 1983; van der Meulen et al., 1991a and b), preprogrammed performance has not been linked to visuoperceptual abilities in clumsy children.

In addition, results from studies of the integrity of visual feedback mechanisms in clumsy children have been equivocal, with some studies suggesting that clumsy and control children are equally able to utilise visual feedback mechanisms (Lord and Hulme, 1988a; Smyth, 1991; van der Meulen et al., 1991a and b). However, it is possible that for simple visuomotor tasks where constraints are minimal, clumsy children use strategies to compensate for inefficiencies and thus reduce measurable effects in the utilisation of visual feedback. If this is the case, visual feedback processing in clumsy children may in fact be impaired and thus requires further investigation.

Most importantly, past investigations into visuomotor control in clumsy children have failed to consider their capacity to utilise visuokinaesthetic feedback mechanisms and distinguish performance in this area from preprogramming abilities. Impaired visuoperceptual processing in clumsy children may affect the accuracy of internal target representation and cross-modal comparisons, resulting in movement error if corrections are based on visuokinaesthetic feedback mechanisms. Visuokinaesthetic feedback control of reaching movements is expected to predominate in conditions where visual feedback has been precluded by removing vision of the moving hand. However, poor performance in these conditions may also be a consequence of initial, preprogrammed errors. To obtain further information about clumsy children's ability to utilise visuokinaesthetic feedback mechanisms, investigations need to compare performance in this condition to performance in conditions that have been modified to reduce the extent of reliance on visuokinaesthetic feedback mechanisms.

There is some evidence that the integrity of right hemisphere function is associated with coordination abilities (Williams et al., 1980; Armitage and Larkin, 1993; Rossi and Zani, 1986) and it is possible that visuoperceptual deficits, deficiencies in motor control and impaired right hemisphere processing might co-occur in clumsy children. However, assessment of lateralisation in clumsy children for the processes underlying skilled movement has not been assessed. Further investigations of hemispheric specialisation for perceptual, preprogrammed and feedback processes in clumsy children are needed to establish the integrity of right hemisphere function in clumsy children.

1.3 The Present Study

The present study sought to investigate the relationship between visuoperceptual deficits, hemispheric specialisation and clumsiness. The major aim was to determine whether visual perceptual disabilities affected performance in underlying processes of visuomotor control, namely: visual feedback processes, visuokinaesthetic corrective mechanisms and preprogramming. The first approach of this study was to investigate mechanisms of visuomotor control in aimed reaching movements in clumsy children by analysing the early and late stages of the movement, and by varying the availability of visual information about the target and the moving hand.

Aimed reaching movements were recorded under three different viewing conditions.

1. Full Vision Performance was assessed while the moving hand and target were continuously in view. Visual feedback mechanisms were expected to be responsible for the high relative accuracy normally achieved under these conditions (Jeannerod, 1986).

2. Restricted View (Hand) In this condition, the target was visible throughout the movement but visual feedback from the moving hand was not available. In this condition, it was expected that subjects would rely on visuokinaesthetic corrective mechanisms to control the reaching movement (Goodale et al., 1986; Pelisson et al., 1986; Prablanc et al., 1992).

3. Restricted View (Hand and Target) In this condition the target was only visible prior to movement initiation and visual information from the moving hand was absent. Thus, the conditions were modified to encourage less reliance on corrective mechanisms such as visual and visuokinaesthetic feedback loops. It is possible that even without a visible target, subjects may have attempted to utilise visuokinaesthetic feedback processes by establishing and remembering an accurate internal representation of the target position (Blouin et al., 1993). However, it has been shown that under these conditions, performance is less accurate than when the target is visible throughout and it appears that memory for the target position is insufficient to allow accurate utilisation of visuokinaesthetic mechanisms (Prablanc et al. 1986). In conditions where availability of feedback information is unreliable, subjects are more likely to preprogram their reaches (Jakobson and Goodale, 1991; Zelaznik et al., 1983). Thus, in the third condition, it was expected that the relative dominance of visuokinaesthetic processes would decrease and that subjects would rely to a greater extent on preprogrammed control.

The integrity of preprogrammed processing was primarily assessed by analysing movement errors in the initial phase of reaching. Since there is an intrinsic sensorimotor delay of about 100 to 150 milliseconds (Keele and Posner, 1968; Carlton, 1981; Elliott, 1993; Jeannerod, 1986), errors in the initial angle of direction for all reaching movements were expected to provide a pure measure of preprogrammed errors resulting from deficiencies in processing of perceptual input, planning or execution. These initial errors were expected to be similar across the three viewing conditions since visual information at the input stage was not varied.

The second approach of this study was to assess the perceptual abilities of the children in the study with a task that was directly related to the reaching movement being assessed. Judgement of the direction of the target relative to the hand is a perceptual skill that is important to the task of aimed reaching. Materials used to assess directional orientation (Benton, 1985) were modified to accommodate the demands of the reaching task and develop a perceptual task that paralleled the perceptual requirements for reaching. In order to assess the effects of processing deficits other than judgement of direction, performance in directional judgement was also used to statistically control for visuoperceptual ability in reaching movements. Thus, for each of the three visual conditions, performance differences attributed to poor directional judgement could be removed by covariate analysis leaving the remaining variation in movement ability to be analysed. Since directional judgement is usually regarded as a right hemisphere ability, the task used to assess perceptual judgement of target direction was also used as a measure of cerebral lateralisation for perceptual abilities.

The third approach of this study was to investigate hemispheric processing for visual perception and motor control in clumsy children. To investigate hemispheric specialisation in reaching movements, children were assessed using both their left and right hands. They were also asked to make reaches to targets in the left and right hemi-space. To maximise the left hand advantage for aimed movements, the target arrangement was similar to that described by Guiard et al. (1983). In the Restricted View (Hand and Target) condition, the target was only seen in the hemi-field of initial presentation and performance in the right and left visual-field could be assessed. In the other two viewing conditions, the target remained on throughout the movement allowing shifts of fixation to the target, and relative performance in hemi-space was being measured.

In summary, this study investigated the relationship between visuoperceptual processing and hemispheric specialisation in the control of reaching movements by clumsy children. To assess the processes most important in determining the skill of the clumsy child in visually guided reaching, the study adopted three approaches. First, performance in preprogrammed, visual and visuokinaesthetic feedback control was assessed by analysing the early and late stages of aimed reaching movements and by systematically varying the amount of visual information available to the child when reaching. Secondly, the ability to judge direction of a target without movement was measured. The measures were used to evaluate hemispheric specialisation for visuoperceptual ability and provided a measure that could be included in the analysis as a statistical control. Finally, differences in the reaching performance of the left and right hands and visual hemi-spaces were evaluated. Any differences in hemispheric specialisation for reaching movements between clumsy and control children could then provide more information about the relative importance of underlying cortical processes.

Although the study was empirically motivated and not designed to test any specific hypotheses, certain results could be anticipated on the basis of the preceding analysis of visuoperceptual and motor skills in clumsy children. Since clumsy children have been shown to demonstrate visuoperceptual impairment, it was expected that they would also demonstrate deficits in judgement of target direction - a visuoperceptual task directly related to reaching. If visuoperceptual deficits were confirmed, it was expected that poor judgement of target position would result in clumsy children making a greater number of errors in preprogramming (errors in the early stages of all reaches) and would also affect visual and visuokinaesthetic feedback processing in the later stages of the movement. In addition, if perceptual deficits and poor coordination in clumsy children are associated with impaired right hemisphere processing, it was anticipated that clumsy children would demonstrate impaired performance in the left hemi-field for judgement of target direction and impaired performance with the left hand and/or left hemi-space in aimed reaching.

Chapter 2

Method

2.1. Experimental Design

This study compared reaching to visual targets by a group of clumsy children with performance by a group of control children matched to the clumsy group on age, sex and handedness. All children completed the following tasks.

1. Screening tests. These included simple tests for the assessment of motor ability, a short form of the WISC-R (Wechsler, 1974) to assess intelligence, and a five item questionnaire to assess handedness.

2. Visuoperceptual test. This test required the subjects to choose the line that pointed in the correct direction to one of six points presented in either the left or right visual-field. 15 trials were completed for each visual-field.

3. Reaching tasks. Reaching performance was assessed in the same experimental environment as the visuoperceptual test, but only two of the targets (one left, one right) were used. The experimental design for reaching performance is summarised in Table 2.1. Children were asked to make a number of aimed reaching movements in the horizontal plane under three different viewing conditions. In the Restricted View (Hand and Target) presentation, the target (Tg) was viewed for only 150 ms at the beginning of the movement and vision of the hand (H) was precluded. In the Restricted View (Hand) presentation, the target was visible throughout the movement but vision of the hand was not available. In the Full Vision presentation, the subject could see the hand and the target throughout the movement. Twenty trials were completed for each viewing condition.

Table 2.1
Summary of the experimental conditions for reaching performance

	TARGET/HAND LATERALITY			
VIEWING CONDITION	**LH/LTg**	**LH/RTg**	**RH/LTg**	**RH/RTg**
Restricted View (H/Tg)	5 trials	5 trials	5 trials	5 trials
Restricted View (Hand)	5 trials	5 trials	5 trials	5 trials
Full Vision	5 trials	5 trials	5 trials	5 trials

In order to investigate the effects of target/hand laterality on reaching performance, the target side and reaching hand were varied. Within each viewing condition, the child was required to make five reaches with the right hand to the right target (RH/RTg), with the right hand to the left target (RH/LTg), with the left hand to the right target (LH/RTg) and with the left hand to the left target (LH/LTg).

For purposes of analysis the experiment was regarded as a three way design: Group (Clumsy, Control) x Viewing Condition (Restricted View (H/Tg), Restricted View (Hand), Full Vision) x Target/Hand Laterality (LH/LTg, LH/RTg, RH/LTg, RH/RTg).

2.2 Subjects

Children were selected from two primary schools in Canberra, Australia. The sample comprised 16 clumsy and 16 normally developing children ranging in age from seven years six months to 12 years 1 month. The experimental group comprised 13 boys and three girls. In this group, three boys were left handed. Children in the control group were matched individually to the children in the clumsy group on age, sex and handedness. All subjects were in age appropriate grades.

The clumsy children were selected by the physical education teacher of the local primary school near the university. He identified children in the school who exhibited motor coordination markedly below the expected level, given the child's age. The children were not physically or intellectually disabled and the physical education teacher was asked not to include any child who was known to have a physical disorder such as cerebral palsy, hemiplegia or muscular dystrophy. All children in this group satisfied DSMIV criteria (American Psychiatric Association, 1994) for Developmental Coordination Disorder: A) the child's performance in motor activities was substantially below that expected by age and intelligence; B) the motor problems were significant enough to interfere with school achievement or activities of daily living and C) the disturbance was not due to a general medical condition such as cerebral palsy, hemiplegia or muscular dystrophy.

The physical education teacher originally identified 17 boys and six girls out of approximately 260 students in Grades two to six. That is, 9% of students in this school population were considered to be clumsy. This is consistent with other studies suggesting that up to 10% of children attending main stream primary schools are labelled clumsy (American Psychiatric Association, 1987; Gubbay, 1975; Laszlo, 1990). The three to one ratio of boys to girls identified as clumsy is also consistent with the literature (Gordon and McKinlay, 1980; Laszlo et al., 1988). Of those children first identified, three girls and four boys did not participate because parental permission was not obtained.

Fourteen children from the control group were selected from the same classroom lists as the clumsy children on the basis of having a birth date within three months of an identified clumsy child of the same sex and handedness.

However, two of the left-handed children in the control group were identified by a physical education teacher from another primary school because no one of a suitable age was available at the first school. These left-handed children were chosen on the basis of being aged within four months of the identified child and were known not to have any coordination difficulties.

2.3 Screening Tests

2.3.1 Motor Tests

Many motor assessment batteries used today are relatively time consuming (e.g. Bruininks, 1978 or Stott, Moyes and Henderson, 1984). However, Gubbay (1978) found that four standardised tests: throwing and clapping, rolling a ball underfoot, threading beads and inserting shapes were sufficient to confirm the presence of undue clumsiness. Lord and Hulme (1987a) also found the performance of clumsy children to be significantly inferior on four motor measures: balancing on one foot, throwing and clapping, skipping and bead threading. Accordingly, a short battery of motor tests was chosen to provide a measure of gross and fine motor skills and confirm the relative difference in motor coordination of the two groups. These four tests were based on standardised perceptual-motor tests and modified to accommodate the constraints of testing time and availability of materials.

1. Balance In this test of static balance, the child was asked to stand on the preferred foot for as long as possible. Time measured in seconds was recorded (60 seconds maximum per trial). This task is commonly used as a measure of motor impairment (Bruininks, 1978; Lord and Hulme, 1987a and b; Stott et al., 1984).

2. Throw-Clap-Catch Throwing and catching tasks have been used to test upper limb coordination (Bruininks, 1978; Elliott et al., 1988; Stott et al., 1984).

In this task, the child was required to catch a tennis ball after throwing it up into the air and clapping both hands together. Each child was given three attempts at each level of difficulty. In the first five levels, the number of claps required increased progressively from 0 to 4. For the sixth level the child was required to clap four times and then catch the ball with only one hand. Testing was discontinued when the child missed the ball three times at one level. The score recorded was the number of successful attempts out of 18 trials (Gubbay, 1975).

3. Bead Threading Bead threading is a common test of manual dexterity requiring the coordination of two hands (Bruininks, 1978; Elliott et al., 1988; Gubbay, 1975; Stott et al., 1984). The child was required to thread 10 plastic coloured beads on to a string as quickly as possible. The beads were 20 mm in diameter with a 2 mm hole. They were threaded onto a shoelace 40 cm long with a stiffened plastic end of 3 cm. The score was the time taken in seconds to thread 10 beads.

4. Purdue Peg Board Performance using peg boards has been commonly used to measure manual speed and dexterity (Bruininks, 1978; Elliott et al., 1988; Stott et al., 1984). In this study, children were required to place pegs in a standard Purdue Peg board as quickly as possible. The pegs were 25 mm long and 2 mm in diameter. The test was administered according to the recommendations of Lezak (1983). Children were required to place as many pegs in a row as they could in 30 seconds, using first their preferred hand and then their non-preferred hand.

2.3.2 Assessment of Intelligence

A short form of the Wechsler Intelligence Scale for Children-Revised (1974) was administered to assess the intellectual capacity of the children. This comprised two Verbal subscales (Similarities and Vocabulary) and two Performance subscales (Block Design and Picture Completion). This short form has a validity coefficient of r = 0.943 with the full scale WISC-R (Sattler, 1982). Although Object Assembly has often been used in the short form by other researchers (e.g. Lord and Hulme, 1987a and b), Picture Completion was chosen for this study because it is a test of visuoperceptual ability that is not confounded by motor capabilities (Lezak, 1983).

Both Similarities and Vocabulary contribute substantially to the verbal comprehension factor and have moderately low correlations with the Performance scale. The Block Design and Picture Completion subtests have high loadings on the perceptual organisation factor and moderately low correlations with the Verbal scale. Thus, these four items provide a relatively independent assessment of verbal and perceptual skills. Separate assessment of verbal and perceptual skills was required because researchers have consistently found that clumsy children have Performance IQ's significantly lower than their Verbal IQ's (Gubbay, 1975; Lord and Hulme, 1987 a and b).

Scores for the four sub-tests were converted to an estimate of the Full Scale IQ by using the recommended formula for transforming scores into a Wechsler-type Deviation Quotient. This procedure weights the individual subtests according to their reliability (Sattler, 1982).

2.3.3 Assessment of Handedness

All children were asked to report their hand preference for five activities on a three point scale (left -1, both-2, right-3). The questions asked were: 1) Which hand do you use to write? 2) Which hand do you use to draw? 3) Which hand do you use to cut with scissors? 4) Which hand do you use to brush your teeth? 5) Which hand do you use to throw a tennis ball? Responses were summed and the total score could range from 5 (extreme left handedness) to 15 (extreme right-handedness). The questions were based on a self-report questionnaire tested on

443 children aged five to nine years by Roszkowski, Snelbecker and Sacks (1982). These five items are the best indices of hand preference for adults (Bryden, 1977). For children, self-reported preference has been shown to be stable over a one month period and the test has good internal consistency (Roszkowski et al., 1982).

2.3.4 Group Effects for Screening Measures

Motor Ability

The means and standard deviations of the scores for the four motor measures are shown in Table 2.2. Also shown is a composite measure of motor ability derived by converting the scores for each motor test into z-scores and then summing these scores for each child. The z values for Beads were reversed scored since this measure was high for poor performance and low for good performance.

Table 2.2
Means and SDs of motor measures

	Clumsy Mean (SD)	Control Mean (SD)	U	p
Pegs	22.31 (4.57)	26.31 (2.15)	51.5	0.004
Beads	36.26 (11.01)	26.00 (3.97)	54.0	0.005
Claps	9.56 (3.97)	13.69 (3.24)	50.0	0.003
Balance	45.11 (19.41)	55.33 (10.04)	78.5	0.030
Zmove	-1.84 (3.50)	+1.84 (1.36)	47.0	0.002

The distribution of Balance in the normal sample was skewed so Mann-Whitney U-tests were employed to avoid the assumptions of parametric tests. Clumsy children performed at a significantly lower level in placing pegs in a peg board (Pegs), threading beads (Beads), throwing/catching/clapping (Claps), balancing on one leg (Balance) and in the composite measure of motor ability (Zmove). Thus, all motor tests discriminated clearly between the clumsy and control children and confirm the existence of clumsiness in the children selected by the physical education teacher. The degree of overlap in motor skill between the two populations could not be assessed because the groups were heterogenous in age, which is a confounding factor.

Intelligence, Age and Handedness Measures

The means and standard deviations for age, handedness, sub-tests of the WISC-R and estimated full-scale IQ are shown in Table 2.3. There were no significant differences between groups for any measure of intelligence. As would be expected from the matching procedure, there were clearly no significant differences between the groups for age and handedness.

Table 2.3.
Means and SDs for age, handedness, sub-tests of the WISC-R and estimated full scale IQ scores

	Clumsy Mean (SD)	Control Mean (SD)	t	p
Vocabulary	11.94 (2.11)	10.88 (2.06)	-1.44	0.160
Similarities	13.44 (1.55)	12.94 (2.89)	-0.61	0.547
Picture Comp.	12.31 (2.06)	12.50 (1.67)	0.28	0.779
Block Design	12.63 (3.32)	13.68 (2.21)	1.06	0.296
Prorated IQ	116.34 (10.42)	115.71 (10.57)	-0.17	0.866
Age(months)	126.0 (13.97)	126.1 (13.14)	0.03	0.979
Handedness	12.8 (3.02)	12.9 (3.80)	0.05	0.959

These results also indicate that the clumsy children in this experimental group had similar intellectual abilities to the control children. There was no evidence of a discrepancy between Verbal and Performance skills on the WISC-R. This is in contrast to other studies which have found that clumsy children frequently have Performance IQs significantly lower than their Verbal IQs (Gubbay, 1978; Hulme et al., 1982a and b; Lord and Hulme, 1987a and b; Walton et al., 1962).

However, it is possible that in this study the inclusion of Picture Completion, a test that is not confounded by motor abilities, reduced the effect of the usually observed difference.

2.4 Apparatus

The apparatus enabled assessment of reaching movements and perceptual judgment of direction to be carried out under matched conditions. It is depicted schematically in Figure 2.1. The equipment design is based on apparatus described by Prablanc, Echalier, Komalis and Jeannerod (1979). Three horizontal Perspex shelves (backed with black cardboard), 5 mm thick, were fixed on a table with separation distances of 27 cm. Additional screening was placed at the back to reduce unwanted light. The lowest shelf (the reaching surface) was mounted at approximately elbow height for a seated subject. The forehead rested against a support, mounted at the edge of the uppermost shelf (the stimulus surface) and the child looked through the gap between the two upper shelves down onto the middle shelf (reflecting surface). Seating was adjustable so that a child could always see and reach for the target easily. All reaching movements used the same starting position indicated by a 13 mm round marker, directly in front of the child, four and a half cm in from the edge of the reaching surface.

A transparent viewing aperture, 34 by 25 cm, was located on the reflecting surface (middle shelf) so as to give a clear view of the starting position and the hand moving on the reaching surface. It was also possible to place a mirror over the viewing aperture so that sight of the reaching surface was removed. Reaching targets were reflections from the stimulus surface on to either the transparent reflecting surface or mirror surface. The heights of the three surfaces were adjusted so that the virtual image of the stimulus surface seen from the reflecting surface was conjugate with the reaching surface. (See Figure 2.2). With the mirror in place, the subject saw the reflected image of the target as if it was on the reaching surface but view of the hand moving was obscured. With the mirror removed, the subject saw the hand through the aperture and the reflected target image.

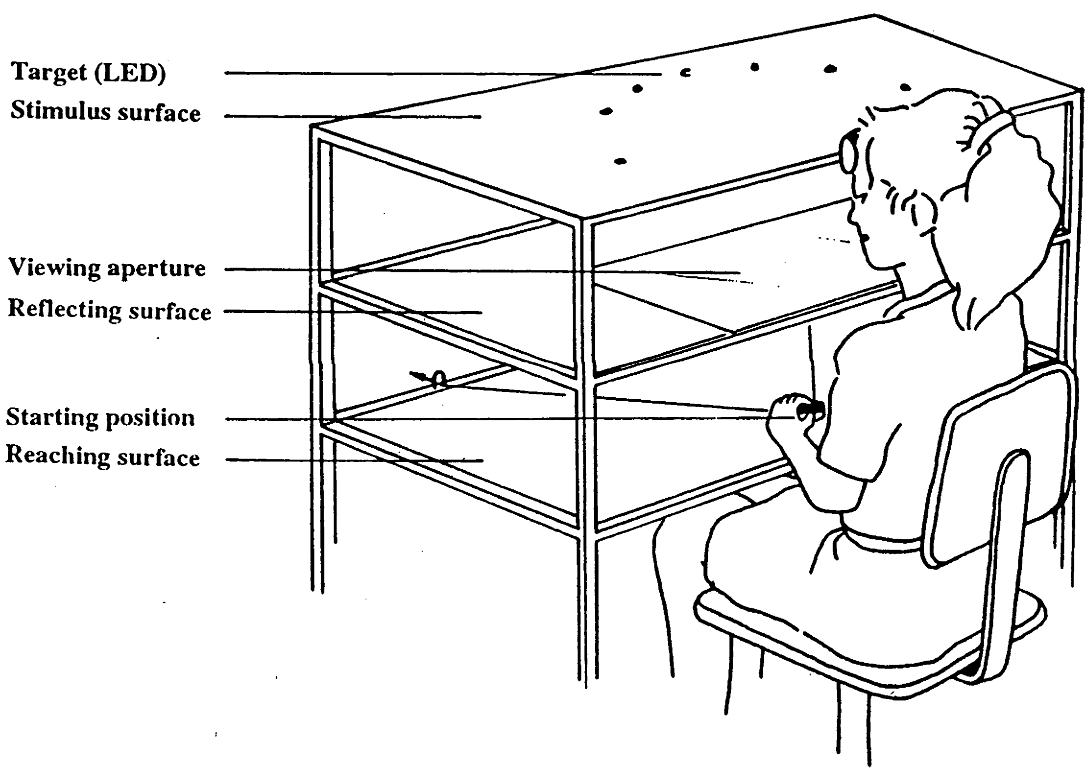


Figure 2.1
The apparatus used to assess reaching movements and perceptual judgement.

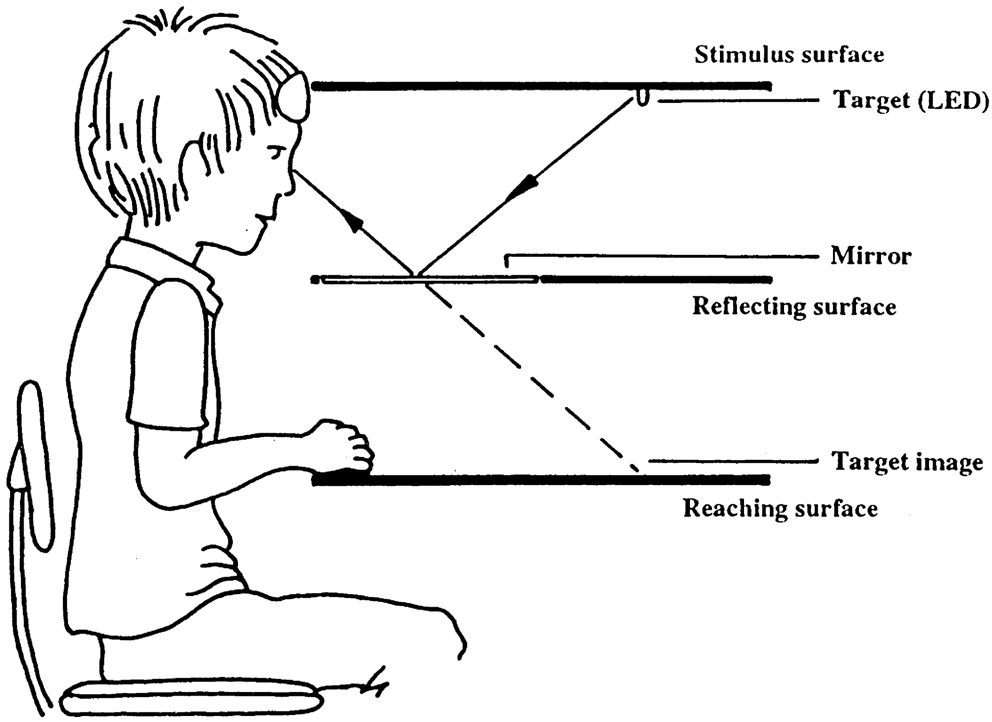


Figure 2.2
The target image as seen by the child when reaching without visual feedback from the moving arm.

The stimuli were LEDs mounted on the under side of the stimulus surface, seen reflected from the middle shelf. The arrangement of possible target images is illustrated in Figure 2.3. There were six possible targets marked by red lights placed on a semi-circle about the starting position (radius = 30 cm). Three targets lay in each hemi-space, separated by angles of 18 degrees measured from the midline. The fixation point, indicated by a green light, lay on the median plane. All six targets were used to assess judgement of target direction. However, in the training session for reaching, only the left and right targets closest to the midline were used and for the experimental assessment of reaching, only the left and right middle targets (36 degrees from the midline) were used.

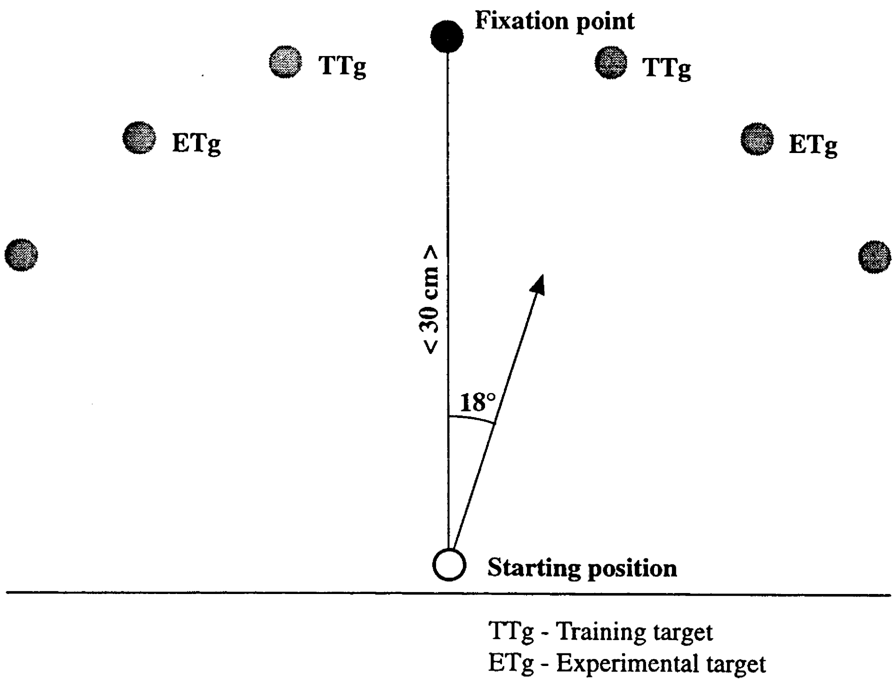


Figure 2.3
The arrangement of target images.

The response card used for the judgement of direction is depicted in Figure 2.4. It was placed on the lower surface directly over the starting position used for the reaching task. The card carried nine, 5 cm lines arranged radially about the starting position. The lines were based on the response cards used by Benton (1985) to assess perception of directional orientation but were modified to point in the direction of the target stimuli.

When making a reaching movement, the child used the index finger and thumb to hold a small (20 mm by 7 mm) peg. The peg was attached to a teflon disc which moved easily over the target surface. Two strings were attached to the centre of the disc and passed horizontally through two eyelets mounted 25 cm to the left and right of the midline at the back of the reaching surface. From the eyelets, each string wound around a small drum which was mounted on the spindle of a potentiometer. Tension on the strings was maintained by elastic. Movement of the teflon disc caused the strings to revolve the drum, generating changes in voltage output from the potentiometers. These changes were read by the A/D converter in the computer and converted to measurements of string length by interpolation in voltage-length calibration tables. The string lengths were then converted to finger positions expressed in terms of an (x,y) coordinate system (x=lateral position, y=distance from starting position). A series of set positions were recorded prior to the experiment to calibrate the apparatus.

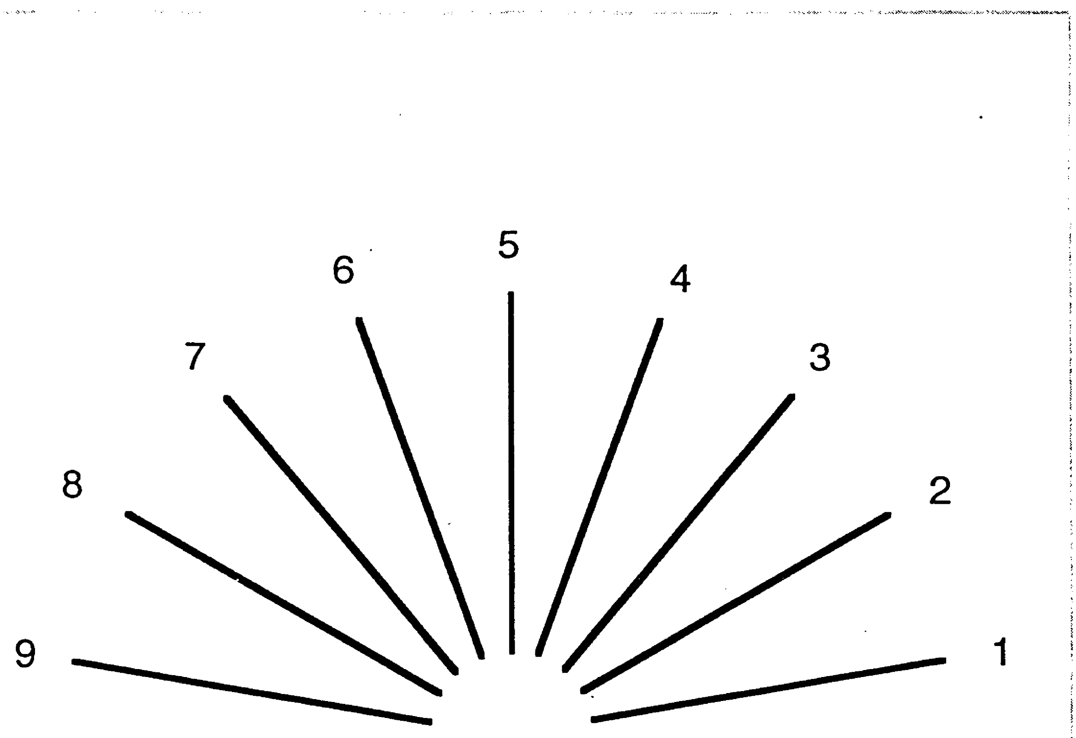


Figure 2.4
Multi-choice options for judging the direction of the target
(Based on response cards used by Benton (1985)).

Each movement was sampled at 200 Hz from the point of trial initiation and the (x,y) record smoothed by computing a weighted running average. Hand Speed at each point was calculated as the Euclidean distance separating its two neighbouring points, divided by the time interval (10 ms) between these points. The starting position of the movement was then defined as the first point of the record with a hand speed exceeding 6 cm/sec. The end-point was defined as the last point on the record where speed was greater than 6 cm/sec. The 'x', 'y' and speed records between the starting position and the end-point were compressed to 50 equally spaced time samples for purposes of data storage.

2.5 Procedure

The children were assessed in two sessions of between 30 and 45 minutes. The first session assessed motor skills, handedness and intellectual ability and was conducted at the primary school. The second session was conducted at the university and assessed judgement of direction and reaching movements. In the majority of cases, the two sessions were conducted within one week of each other. However, for six children the sessions were conducted approximately six weeks apart. This occurred because school holidays intervened before the reaching apparatus was available. For these children, age was taken to be from the time of assessment of reaching movements (except for standardisation of scores for WISC-R subtests).

Assessment of Handedness, Motor and Intellectual Abilities

All children received the tasks in the same order. Intellectual and motor tasks were mixed to maintain the interest and attention of the child. The order of task completion was Vocabulary, Bead Threading, Picture Completion, Balance, Block Design, Throw-Clap-Catch, assessment of handedness, Similarities and Purdue Peg Board. The WISC-R was administered according to standardised procedures.

Perceptual Judgement of Direction

At the beginning of each trial in the judgement of direction task, the child was asked to fixate on the green light positioned at the midline. The trial was initiated manually by pressing a switch connected to the computer. One of six possible targets then lit up briefly for 150 ms, in an order randomly determined by the computer. The subject was able to inspect the response card freely to make a judgement and then indicated a response by pointing to an appropriate line on the card. The number of the line was then entered into the computer for data storage. Five trials for each target were presented, making a total of 30 trials.

Assessment of Reaching

The subject was given the opportunity to practice reaching before assessment began, to reduce the possibility of learning effects. Two reaches were demonstrated by the researcher, one to each side. The child was then shown how to hold the peg and encouraged to move it over the surface to get a feel for the movement. A training session of 12 reaches was then completed using two targets different from those in the experimental session (to reduce transfer effects). Starting with the Full Vision condition (complete visual information from the target and hand available), one reach for every treatment combination was made.

The instructions for the training session and experimental sessions were identical. Subjects were instructed to move the finger to the target "as smoothly and as accurately as possible". Before each movement they were asked to check that they were on the starting position and to then fixate on the green light located in the midline. Before each trial, they were given a verbal signal ("ready") and about one second later the target lit up. Each trial was initiated manually by the experimenter. Trial selection, turning on of stimuli and data measurement were controlled by the computer.

In the experimental session, assessment of reaching performance began with 20 trials in the Restricted View (Hand and Target) presentation. The target duration was for 150 ms at the beginning of the movement and the mirror was placed over the viewing aperture so that vision of the moving hand was precluded. Five trials for each combination of left and right hand and left and right target were randomly presented by the computer.

Twenty trials for the Restricted View (Hand) presentation were then completed. For these trials the target light was on for the duration of the movement, although vision of the moving hand was still precluded by the mirror. Finally, 20 reaching movements in the Full Vision presentation were completed. In this condition, the targets were visible for the entire movement and the viewing aperture was open so that the hand moving to the target could be observed. For both the Restricted View (Hand) and Full Vision presentations, five trials for each combination of left and right hand and left and right target were randomly sequenced by the computer.

In order to avoid transfer of knowledge about target location from the task performed with visual feedback to the tasks performed without visual feedback, the non-visual trials were applied before the visual trials. Thus, the treatment levels for the Viewing Conditions were always applied in the same order: Restricted View (Hand and Target), Restricted View (Hand), Full Vision. There is evidence to suggest that performing the non-visual conditions first does not contribute to any improvement observed in the visual condition (Bard et al., 1990). In particular, precluding sight of the hand means that the child does not receive information on the success of the accuracy of the reach and thus learning effects are reduced. The use of additional target positions in the experimental session would also have reduced potential carry-over effects and enabled full randomisation, and future studies may be able to adopt this methodological strategy.

2.6 Data Analysis

2.6.1 Exclusion of Movements Prior to Data Analysis

Movements were only included in the analysis if the movement time was less than two seconds. This criterion was chosen on the basis that strategies adopted for very long movements are likely to be different from those used for the simple aimed reaches made in the majority of cases. This criterion primarily only affected two children, one from the clumsy group and one from the control group, who both adopted excessively slow and careful movement strategies.

Movements involving false starts, where a small jerk occurred without any distance being covered, were also excluded using this method because in these cases the movement time was incorrectly calculated by the computer. The movement was also excluded if the child stopped during the course of the movement. On a few occasions, the child did not move consistently in the approximate direction of the target. For example, on one occasion a child from the control group made a loop-the-loop approach towards the target. When this occurred, the child was cautioned and told to move in a straight line towards the target. These movements were not analysed because they could not be regarded as one simple aimed reaching movement.

The mean number of movements excluded from the analysis was 6.50 ($SD = 4.59$) for clumsy children and 3.81 ($SD=3.47$) for control children. Clumsy children made significantly fewer successful movements than did control children ($U=70.5$, $p<0.05$). Mann-Whitney tests were employed because the data indicated moderate skewness. At this gross level of analysis, clumsy children demonstrated a smaller proportion of smooth, direct movements, and it is arguable that by excluding less successful movements, differences between groups in the underlying components of performance may have been attenuated. Nevertheless, imposing strict criteria for inclusion in the data analysis ensured that the movements analysed are indeed representative of simple goal directed reaching.

2.6.2 Measures for the Perceptual Task

Number of Visual Errors This variable was calculated as the number of incorrect answers made from 30 trials when choosing the line that best pointed to a target in the judgement of direction task.

Absolute Visual Error This variable was an indicator of the extent of inaccuracy in response. It was calculated as the sum of the deviation scores for 30 trials in the judgement of direction task. A deviation score could range from zero to seven for each trial, with one unit equal to 18 degrees.

Number Lateralisation Index The Number of Visual Errors made in each visual-field were also determined for each visual-field. A lateralisation index for Number of Visual Errors was then calculated according to the formula, (R-L)/(R+L)*100. This formula calculates a percentage difference score that allows the child's overall level of performance to be taken into account when assessing lateralisation differences (Lewandowski and Kobus, 1986).

Absolute Lateralisation Index The Absolute Visual Error for each visual-field was also determined. A lateralisation index was then calculated for Absolute Visual Error in the same manner as for the Number Index.

2.6.3 Measures of Reaching Performance

A data analysis program allowed the movement path and speed time curve of each reach to be displayed on screen so that the experimenter could view the record. Examples of the movement records obtained for a clumsy and a normal child are depicted in Figure 2.5. For each group of movements, seven measures were calculated to give an indication of performance under each treatment condition. Because of the detailed data record, a number of alternative measures could have been calculated. However, other measures that may have been relevant (for example, linearity of the movement path and absolute end-point error) were found to be highly correlated with the measures already taken. Thus, for the purposes of simplifying analysis, only the following seven measures are reported.

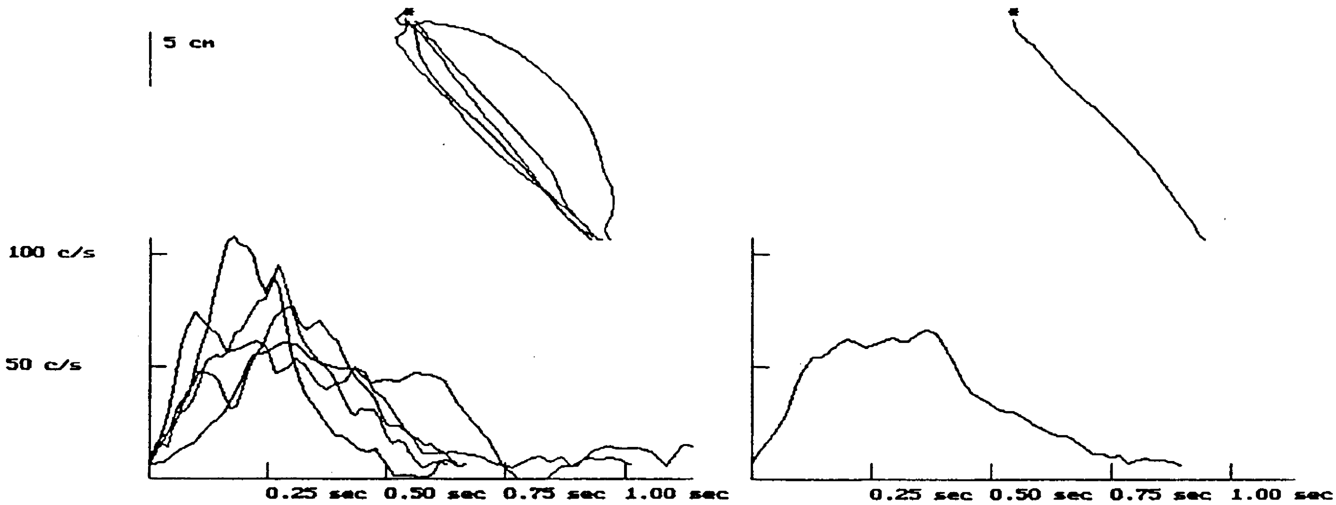
2.6.3.1 Planning

Reaction Time was seen as a measure of the time taken to process information in order to produce a required response (Magill, 1989) and thus was regarded as a measure of planning. It was assessed by measuring the interval in the time recordbetween the start of the signal and the start of the movement. The score was then averaged for each block of trials.

2.6.3.2 Temporal Efficiency

Movement Time was taken as a good measure of overall efficiency of the movement. Speed/accuracy trade-offs in reaching movements (Fitts, 1954) mean that inefficiencies in movement control during the movement could be reflected in slower movement times as the child makes efforts to compensate for difficulties. The time in seconds from the movement starting position to the movement end-point was calculated and then averaged for each block of trials.

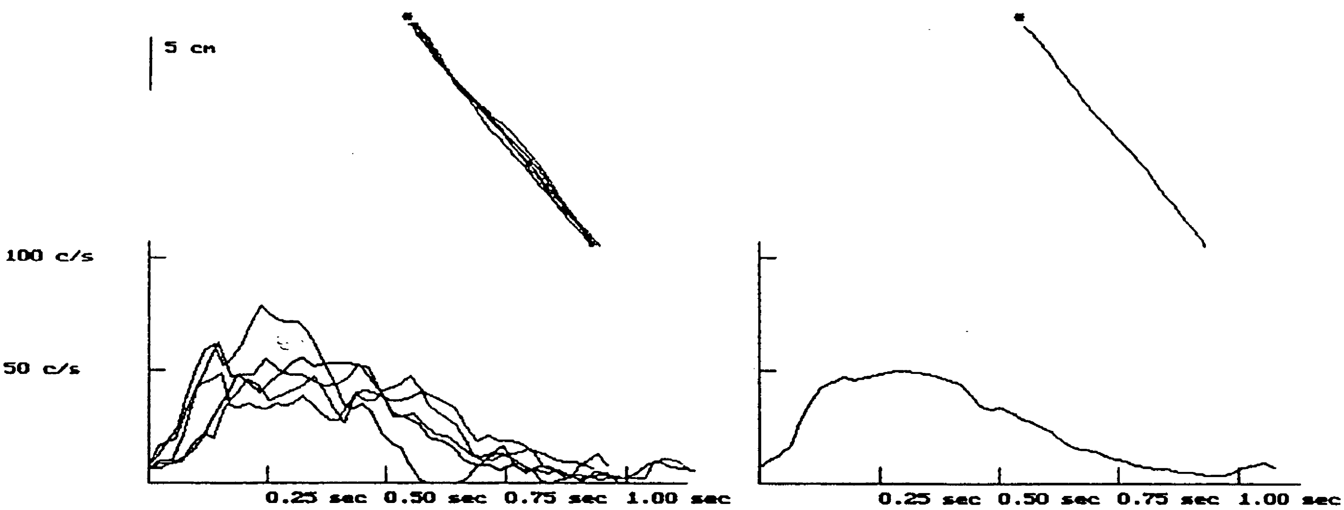
CLUMSY CHILD
Velocity (cm/s) and distance (cm) records



a) Individual Movement Records

b) Averaged movement record (5 trials)

NORMAL CHILD
Velocity (cm/s) and distance (cm) records



a) Individual Movement Records

b) Averaged movement record (5 trials)

Figure 2.5
Sample movement records for a clumsy and normal child, both age 11 years (Full Vision condition, LH/LTg).

2.6.3.3 Spatial Accuracy

Initial Error was defined as the average of the absolute angle separating the line of initial direction from the actual direction of the target (See Figure 2.6). The line of initial direction was determined for each movement by fitting a linear regression line to the set of coordinate pairs representing the first 5 cm of the movement.

Mean Error provides an indication of end-point systematic error and was calculated as the distance between the average end-point coordinate and the target position for each block of trials.

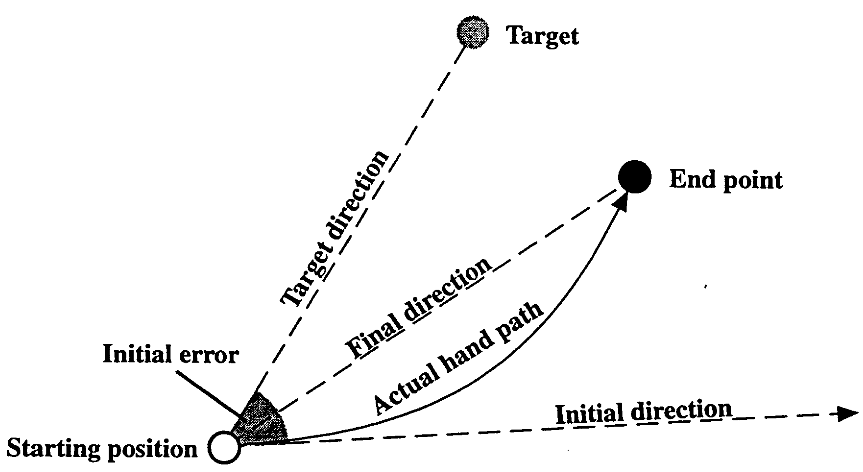


Figure 2.6
Analysis of hand direction and calculation of Initial Error.

2.6.3.4 Consistency of Trajectory

Initial Scatter is an indication of the consistency and control of the initial direction of the movement and was calculated as the standard deviation of the angle of initial error in reaching for each block of trials.

Halfway Scatter was calculated as the scatter of the halfway point of each trial and was intended to provide an indication of consistency and control of reaching halfway through the reach. The halfway point was regarded as the point between the starting position and final end-point, exactly half the distance along the actual path travelled. Scatter was calculated as the square root of the mean of the radial distances (r) of the individual halfway points from their mean position.

$$\text{scatter} = \sqrt{\frac{\sum r^2}{N}} = \sqrt{\text{var}(x) + \text{var}(y)}$$

End Scatter is a measure of precision of performance in terms of end-point variability. As for halfway scatter, it was provided by the square root of the mean of the radial distances of the individual end-points from their mean position.

2.7 Statistical Analysis

For the perceptual task only simple group comparisons were performed. Comparisons for all perceptual measures (Number of Visual Errors, Absolute Visual Error, Number Lateralisation Index and Absolute Lateralisation Index) were conducted using Mann Whitney tests because assumptions of normality were not met. The distributions of these variables showed moderate skewness.

Global analysis of reaching measures was carried out by using a repeated measures analysis of variance with Group (2 levels) as the between subjects factor.

Viewing Condition (3 levels) and Target/Hand Laterality (4 levels) comprised the within subjects factors. This analysis was run separately for Reaction Time, Movement Time, Initial Error, Mean Error, Initial Variability, Halfway Scatter and End Scatter.

Repeated measures analysis of variance was used for the performance variables despite some moderate violations of assumptions. The distribution of overall Reaction Time, Movement Time and Initial Error for each group demonstrated moderate skewness. However, an inspection of the data revealed that no scores were greater than three standard deviations from the mean. Since it was felt to be important to retain meaningful measurement units for analysis, these variables were not transformed. Repeated measures analysis of variance has been shown to be robust to modest violations of normality if the violation is not created by outliers (Tabachnick and Fidell, 1983).

In some analyses, assumptions of symmetry for repeated measures analysis of variance were not always met. (SPSS Inc, 1988). If a significant univariate result was obtained and Mauchley Sphericity tests indicated that the assumption of compound symmetry for the variance-covariance matrix was not satisfied, Huynh-Feldt epsilons were used to adjust degrees of freedom for the F tests and reduce the chance of making a type 1 error (Kirk, 1982, Norusis, 1988). In cases where Box's M test ($p < 0.01$) suggested that variance/covariance matrices were not equal between groups at all levels, the pattern of multivariate results (which does not rely on the symmetry assumption) verified the univariate results and only the latter have been reported.

Chapter 3

Results

The results are presented in three main sections. The first section analyses group differences and laterality effects in judgement of target direction. The second section presents the results from the analyses of variance for the seven measures of reaching performance. The third section further examines group differences in measures of reaching performance by including a measure of perceptual judgement as a covariate in the analysis.

3.1 Judgement of Target Direction

3.1.1 Group Differences

The means and standard deviations of the Number of Visual Errors and the Absolute Visual Error in the judgement of target direction are presented in Table 3.1. The clumsy children made a significantly greater number of visual judgement errors than the control children and the absolute error for visual judgement was significantly greater. The scores obtained by clumsy children were almost double those of the control group. These results suggest that the clumsy children would perform more poorly in visual tasks which involve judgement of directional orientation.

Table 3.1
The Number of Visual Errors and Absolute Visual Error in judgement of target direction

	Clumsy Mean (SD)	Control Mean (SD)	Mann-Whitney U	p
Number of Errors	5.4 (5.8)	2.7 (3.0)	70.5	0.028
Absolute Error (18^{o}units)	6.3 (7.7)	3.3 (3.7)	76.0	0.047

3.1.2 Lateralisation of Judgement of Target Direction

The means and standard deviations of the lateralisation indices (Number Lateralisation Index and Absolute Lateralisation Index) are shown in Table 3.2. These scores represent the difference between left and right visual-field performance in the judgement of target direction, a negative score indicating more errors in the left visual-field. There were no significant differences between the groups, indicating that the clumsy and control children did not differ in the extent to which their perceptual performance was lateralised. Furthermore the indices for both groups did not differ significantly from zero. Thus, contrary to expectations, performance in this task did not exhibit a consistent lateralisation pattern that favoured the left visual-field. Both normal and clumsy children made a similar number of errors in the two fields.

Table 3.2
Differences in right and left visual-field performance in the judgement of target direction

	Clumsy Mean (SD)	Control Mean (SD)	Mann-Whitney U	p
Number Lateralisation	- 1.0 (34.4)	- 9.5 (48.3)	119.0	0.72
Absolute Lateralisation	- 0.7 (36.4)	-10.2 (49.6)	120.5	0.76

3.2 Reaching Performance

Repeated measures analysis of variance with Group (2) as a between subjects factor and Viewing Condition (3) and Target/Hand Laterality (4) as within subjects factors was used to analyse the measures of reaching performance. Analyses were conducted separately for Reaction Time (RT), Movement Time (MT), Initial Error, Mean Error, Initial Scatter, Halfway Scatter and End Scatter. Where significant main effects and interactions occurred for Viewing Condition and Target/Hand Laterality, comparisons between means were performed to examine in more detail differences of theoretical interest. For Viewing Condition, simple comparisons between performance in the Restricted View (Hand and Target), Restricted View (Hand) and Full Vision conditions were conducted. For Target/Hand Laterality, comparisons were made between: 1) the left hemisphere condition (RH/RTg) and the right hemisphere condition (LH/LTg), 2) the left and right hands, 3) the left and right targets and 4) crossed (RH/LTg and LH/RTg) and uncrossed conditions (RH/RTg and LH/LTg). Dunn-Sidak procedures were used to evaluate the significance of the follow-up t tests (Howell, 1987, Kirk, 1982).

The means and standard deviations for the measures of reaching performance in each cell are presented fully in Appendix A and complete results for the analyses of variance are shown in Appendix B. Relevant results are discussed further in the following section.

3.2.1 Reaction Time

The average reaction time for the children in this study to initiate a reaching movement was 471 milliseconds (SD=123). The difference between the clumsy and the control groups was not significant. Both groups took a similar amount of time to process information before initiating a response regardless of the viewing condition and the hand or target used.

Table 3.3 presents the means and standard deviations for RTs under the different laterality conditions. RTs varied significantly depending on which hand and target combination was used ($F=5.37$ $df=3,77$ $p<0.01$). Further analysis of this effect indicated that RT was significantly longer for uncrossed reaches than for crossed reaches ($t=3.77$ $df=31$ $p<0.01$). Other target/hand comparisons were not significant.

Table 3.3
Means and SDs for RTs, MTs, Initial Error and Mean Error made in the Target/Hand Laterality conditions

	Uncrossed		Crossed	
	LH/LTg	RH/RTg	LH/RTg	RH/LTg
RT (msecs)	475 (101)	495 (117)	448 (100)	466 (96)
MT (msecs)	726 (246)	747 (289)	816 (241)	809 (267)
Initial Error (degrees)	6.10 (3.88)	6.02 (2.65)	12.54 (3.52)	10.64 (4.62)
Mean Error (cm)	2.02 (0.80)	1.69 (0.84)	2.27 (0.94)	2.14 (0.70)

3.2.2 Movement Time

The average duration of a reaching movement for the children in this study was 774 milliseconds (SD=292). The difference between the clumsy and control groups was not significant. Whatever the condition, both groups took similar amounts of time to reach a target.

Figure 3.1 presents the means of MT for the three viewing conditions for both groups combined. MTs varied significantly with the viewing condition ($F=8.32$ $df=2,54$ $p<0.01$) and further analysis indicated that movement time was significantly faster in the Restricted View (Hand and Target) condition than in the Restricted View (Hand) condition ($t=3.06$ $df=31$ $p<0.01$). However, the two conditions with the target visible throughout the movement (Restricted View (Hand) and Full Vision) did not differ significantly from each other.

Table 3.3 shows the means and standard deviations for MT under the different laterality conditions. Movement duration varied significantly with target/hand laterality ($F=12.44$ $df=3,79$ $p<0.01$). Analysis to identify the source of these differences showed that crossed reaches were significantly slower than uncrossed reaches (t=-5.56 df=31 p<0.01) but no significant differences were observed for the other comparisons.

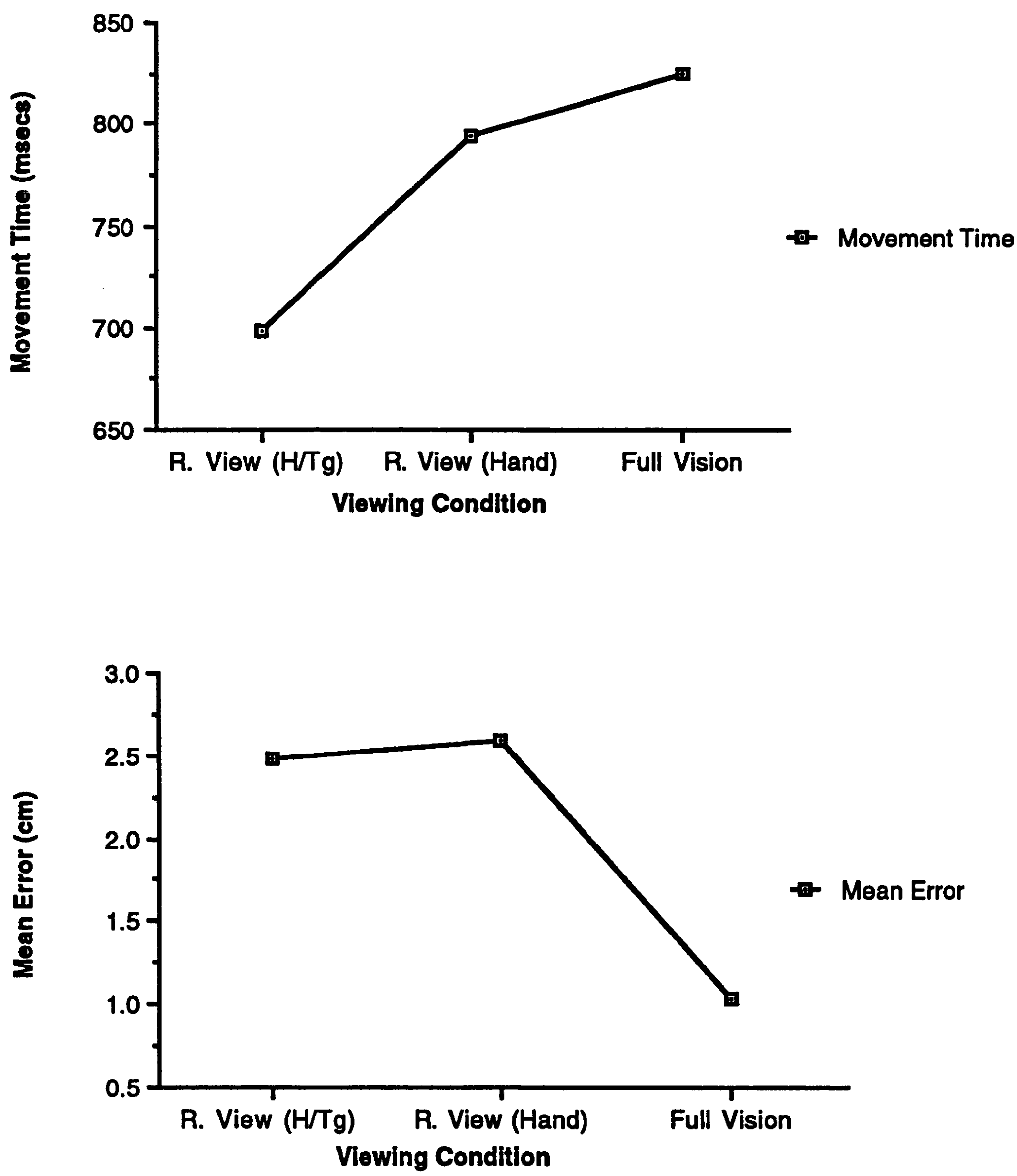


Figure 3.1

Mean Scores for Movement Time and Mean Error for all subjects in the Viewing Conditions

3.2.3 Systematic Spatial Error

Initial Error

Analyses of main group effects showed no significant differences between the performance of clumsy and control children in absolute measures of Initial Error. Overall, the two groups did not differ in the extent of angle error when initiating reaching movements.

The means and standard deviations for Initial Error under the different laterality conditions are presented in Table 3.3. Initial Error varied significantly across hand and target combinations ($F=32.29$ $df=3,90$ $p<0.001$). Further analysis indicated that Initial Error was significantly greater for crossed reaches than for uncrossed reaches ($t=-9.08$ $df=31$ $p<0.01$). Comparisons between hands, targets and hemispheric conditions did not show significant differences.

A significant third order interaction for Group by Viewing Condition by Target/Hand Laterality was observed ($F=2.21$ $df=6,180$ $p=0.04$). However, planned comparisons between means failed to indicate any significant differences. An inspection of the data suggested that clumsy children made a greater number of errors for LH/LTg in the Restricted View (Hand) condition, and for RH/RTg in the Full Vision condition although these differences did not reach significance.

Mean Error

The mean end-point error for aimed reaching movements did not vary significantly between the clumsy and control groups. Whatever the condition, both groups demonstrated similar average errors at the end of the reach.

Figure 3.1 also shows means of the Mean Error for the three viewing conditions. Mean Errors were observed to change significantly depending on the viewing condition ($F=60.56$ $df=2,60$ $p<0.001$). Mean Error did not differ significantly in the conditions when the moving hand could not be seen (Restricted View (Hand and Target) and Restricted View (Hand)). However, as expected, there was a significant improvement in error rate when full visual information was available (t=9.98 df=31 p<0.01).

Table 3.3 also depicts the means and standard deviations for Mean Error for the laterality conditions. Mean Error varied significantly with target/hand laterality (F=3.37 df=3,90 p=0.02). Crossed reaches were less accurate than uncrossed reaches (t=2.76 df=31 p<0.05) but no significant differences were observed for the other laterality comparisons. A significant Viewing Condition by Target/Hand Laterality interaction was also observed for Mean Error (F=3.10 df=6,180 p=0.007). Table 3.4 shows that crossed reaches were significantly more inaccurate for the Restricted View (Hand) (t=2.72 df=31 p<0.05) and Full Vision (t=2.90 df=31 p<0.05) conditions but a significant effect for target/hand laterality was not observed for the Restricted View (Hand and Target) condition.

Table 3.4
Means and SDs for Mean Error in the various combinations of Target/Hand Laterality and Viewing Condition

	Uncrossed		Crossed	
	LH/LTg	RH/RTg	LH/RTg	RH/LTg
Mean Error (cm)				
Restricted View (H/Tg)	2.40 (1.30)	2.23 (1.29)	2.59 (1.29)	2.69 (1.27)
Restricted View (Hand)	2.52 (1.38)	2.08 (1.37)	3.27 (1.57)	2.50 (1.23)
Full Vision	1.15 (0.54)	0.77 (0.63)	0.95 (0.62)	1.24 (0.66)

3.2.4 Consistency of Trajectory

Initial Scatter

Figure 3.2 presents the group means for Initial Scatter under the three viewing conditions. A significant main effect for Group was observed for initial variability in the movement (F=13.34 df=1,30 p=0.001). The clumsy children showed almost one and a half times more variability in the early stages of reaching. Moreover, this effect was entirely independent of the viewing conditions and the hand or target used.

Halfway Scatter

Figure 3.2 also depicts the group means for Halfway Scatter under the three viewing conditions. A large, significant main effect for Group was found for halfway variability in the movement (F=14.23 df=1,30 p=0.001). The clumsy children were significantly more variable in the middle stages of reaching under all conditions.

A significant main effect for Viewing Condition was also observed for Halfway Scatter (F=3.37 df=2,60 p=0.041). Simple contrasts indicated that scatter was significantly less in the Full Vision condition than in the Restricted View (Hand and Target) condition (t=2.53 df=31 p<0.05). This suggests that at the halfway mark in reaching, both groups were starting to utilise visual information, if it was available, to correct reaching performance.

End Scatter

The group means for End Scatter under the three viewing conditions are also shown in Figure 3.2. Clumsy children were significantly more variable in end-point reaching than control children (F=16.57 df=1,30 p<0.001).

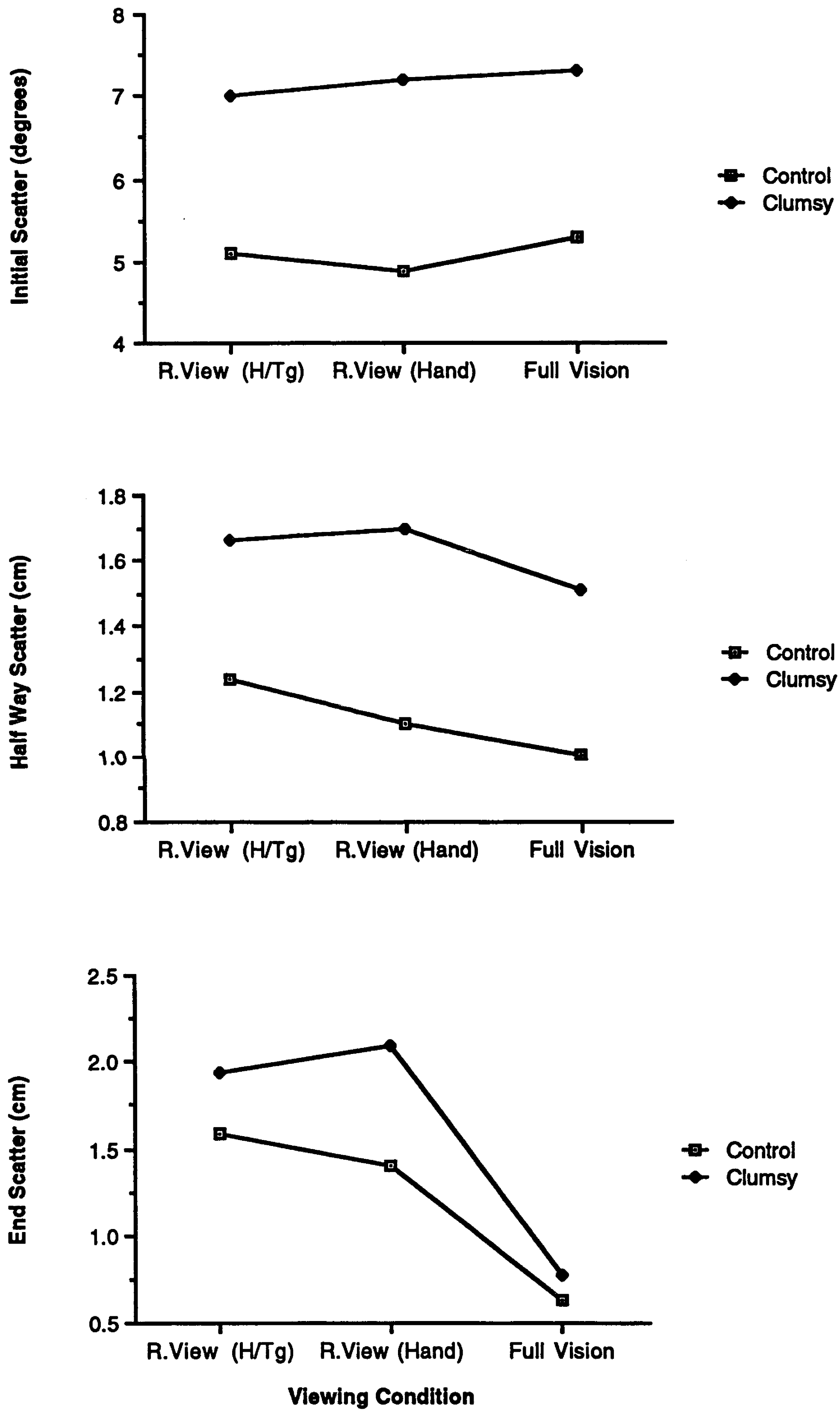


Figure 3.2

Means for Initial Scatter, Halfway Scatter and End Scatter in the Viewing Conditions.

Follow up analysis showed that significant differences between the clumsy and control children were observed for the Restricted View (Hand and Target) and Restricted View (Hand) conditions and, despite the relatively greater improvement by clumsy children, still remained in the Full Vision condition (See Table 3.6).

End Scatter varied significantly with Viewing Condition ($F=137.47$ $df=2,60$ $p<0.001$) and there was also a significant interaction between Group and Viewing Condition ($F=7.02$, $df=2,60$ $p=0.002$). The control group were significantly better in the Restricted View (Hand) condition compared to the Restricted View (Hand and Target) condition ($t=2.80$ $df=15$ $p<0.05$). Performance was also better in the Full Vision condition than the Restricted View (Hand) condition ($t=10.44$ $df=15$ $p<0.01$). This suggests that the control children were able to use visual information from both the target and the moving hand, to improve performance at the end of the reach. However, for the clumsy child, performance actually deteriorated (albeit not significantly) when the target was visible compared to the Restricted View (Hand and Target) condition. It was only in the Full Vision condition that clumsy children showed an improved performance relative to the other conditions ($t=9.67$ $df=15$ $p<0.01$).

Figure 3.3 depicts the End Scatter means for clumsy and control children in the various hand and target combinations. There was a significant main effect for Target/Hand Laterality ($F=3.06$ $df=3,90$ $p=0.032$). There was also a significant interaction between Group and Target/Hand Laterality ($F=2.85$, $df=3,90$ $p=.042$), which suggests that the differences in the performance of clumsy and control children were influenced by task lateralisation. The laterality effects for each group were analysed separately. The control subjects did not demonstrate any significant effects for target/hand laterality. In contrast, clumsy children performed significantly better with the right hand than the left hand ($t=2.69$ $df=31$ $p<0.05$), and LH/LTg was significantly inferior to RH/RTg ($t=-2.77$ $df=31$ $p<0.05$). The performance of the clumsy children deteriorated significantly relative to the control children when trials were conducted in right hemisphere dominant conditions.

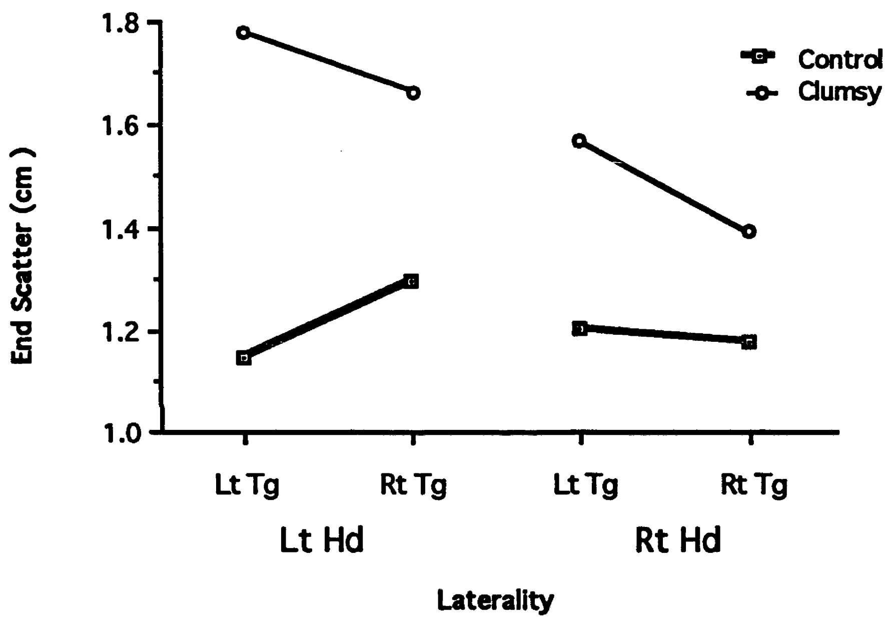


Figure 3.3
Mean group scores for End Scatter in the Target/Hand Laterality conditions.

3.3 The Contribution of Visual Judgement to Reaching Performance

To explore the contribution of visual judgement to reaching performance, visuoperceptual ability was statistically controlled by using error in directional judgment as a covariate in the analysis of variance for Initial, Halfway and End Scatter. If accurate judgement of target direction were the sole determinant of differences in reaching movements, the significance of the group differences observed in the three measures of consistency were expected to be eliminated when the perceptual measure was included as a covariate.

The relationship between perceptual and motor abilities was first examined by computing correlations of the measures of movement consistency with Number of Visual Errors and Absolute Visual Error. These coefficients are presented in Table 3.5. Separate correlations were calculated for End Scatter in the Restricted View (H/Tg), Restricted View (Hand) and Full Vision conditions because of the significant Group by Viewing Condition interaction observed in earlier analysis. For clumsy children, Absolute Visual Error was significantly related to End Scatter in the Full Vision condition. No other relationships were significant.

Number of Visual Errors and Absolute Visual Error were highly significantly correlated for both the clumsy group ($r=0.98$, $p<.01$) and the control group ($r=0.92$, $p<0.01$). This suggests that the two variables are essentially measuring the same process. Since Absolute Visual Error was also significantly related to reaching performance in clumsy children, only this variable has been reported in the covariate analysis. Results using Number of Visual Errors as the covariate, replicated the ANCOVA using Absolute Visual Error, and are presented fully in Appendix C

Table 3.5
Correlations between measures of reaching consistency and judgement of target direction

	Clumsy		Normal	
	Number of Errors	Absolute Error	Number of Errors	Absolute Error
Initial Scatter	0.36	0.33	0.30	0.22
Halfway Scatter	0.47	0.44	-0.09	-0.08
End Scatter				
Restricted View (H/Tg)	0.18	0.14	-0.26	-0.29
Restricted View (Hand)	0.05	0.01	0.05	0.02
Full Vision	0.47	0.55*	-0.05	0.11

* p<0.05

Means and standard deviations of Initial Scatter and Halfway Scatter are shown in Table 3.6. As mentioned earlier, analysis of variance yielded significant group differences for these two measures. Analysis of covariance using Absolute Visual Error as the covariate resulted in the adjusted group means presented in Table 3.7. The table shows that highly significant group differences remained after statistically controlling for ability to make judgements of target direction.

Table 3.6 also shows the means and standard deviations of End Scatter in each of the viewing conditions. Separate ANCOVAs were performed for each viewing condition because End Scatter showed a significant Group by Viewing Condition interaction. Global analysis could not be performed since only one value of directional judgement was available for each subject. Table 3.7 indicates that significant group differences remained in the Restricted View (Hand and Target) and Restricted View (Hand) conditions after the inclusion of the covariate.

In the Full Vision condition, the inclusion of Absolute Visual Error accounted for a significant proportion of the explained differences and, after inclusion of the covariate in the analysis, the main effect for group was no longer significant. This suggests that the differences between groups observed at the end of the movement when full visual information was available, can be attributed to differences in the ability to make accurate perceptual judgements about target direction.

Table 3.6
Means and SDs for Initial Scatter, Halfway Scatter and End Scatter

	Clumsy		Normal			
	Mean	(SD)	Mean	(SD)	F	p
Initial Scatter (deg)	7.18	(2.11)	5.10	(0.87)	13.34	<0.01
Halfway Scatter (cm)	1.62	(0.51)	1.11	(0.17)	14.23	<0.01
End Scatter (cm)						
Restricted View (H/Tg)	1.94	(0.51)	1.59	(0.30)	5.59	0.03
Restricted View (Hand)	2.10	(0.55)	1.41	(0.24)	20.27	<0.01
Full Vision	0.78	(0.20)	0.63	(0.15)	4.89	0.04

Table 3.7
Means for Initial, Halfway and End Scatter adjusted for the covariate (Absolute Visual Error)

	Clumsy	Normal	F	p
Initial Scatter (deg)	7.05	5.22	10.46	<0.01
Halfway Scatter (cm)	1.59	1.15	11.21	<0.01
End Scatter (cm)				
Restricted View (H/Tg)	1.93	1.60	4.84	0.04
Restricted View (Hand)	2.09	1.41	18.34	<0.01
Full Vision	0.76	0.65	2.91	0.10ns

Chapter 4

Discussion

4.1 Summary of Results

The main results of the analysis in Chapter Three were:

1) The clumsy children made significantly more errors than control children in judgement of target direction, a visuoperceptual task directly related to reaching.

2) The clumsy children were significantly more inconsistent than control children in the initial phase of reaching (Initial Scatter). Group differences in initial variability were independent of the viewing conditions.

3) The clumsy children were significantly more variable than the control group at the end of the reach (End Scatter) under all conditions. A significant interaction between Group and Viewing Condition was also observed. The control children showed better performances in both the Restricted View (Hand) and Full Vision conditions compared to the Restricted View (Hand and Target) condition. On the other hand, the clumsy children only demonstrated an improved performance in the Full Vision condition.

4) There was no difference in the end-point performance (End Scatter) of the clumsy and control children in the Full Vision condition after corrections for differences in the ability to judge target direction were made by ANCOVA. However, for the early stages of reaching movements (Initial Scatter) and under restricted viewing conditions, visuoperceptual ability did not contribute significantly to differences between the group.

5) There were no significant differences between the clumsy children and the control group for reaction time (RT), a measure of planning. There were also no significant differences between the clumsy and control children for movement time (MT), a measure of temporal efficiency.

6) The study did not obtain evidence to suggest that perception of visuospatial information was lateralised. Both groups made a similar number of errors in the left and right visual-fields for judgement of target direction. However, the clumsy children were significantly more inconsistent when reaching with the left hand to the left target, than when reaching with the right hand to the right target. In contrast, the control group showed no laterality effects for reaching movements, and performed equally well in all target/hand combinations.

The main focus of this study was to investigate the relationship between visuoperceptual deficits in clumsy children and performance in underlying processes of visuomotor control. These results confirm both the existence of visual deficits in clumsy children and the occurrence of specific problems in reaching in these children. The results suggest that their motor deficits are partially explainable by their visual deficits. However, there appears to be additional contributive factors.

4.2 Deficits in Visuoperceptual Abilities

The finding that clumsy children were inferior in judging the direction of a target supports earlier evidence which indicates that clumsy children are impaired in the perceptual processing of visuospatial information (Lord and Hulme, 1987a; Lord and Hulme, 1988a; Hulme et al., 1982a and b). Performance of almost all motor skills requires processing of some level of visuospatial information, and a deficiency in visual processing could contribute to poor motor output. The presence of visuoperceptual deficits in this sample of clumsy children provided further support for the contention that visual perceptual impairments affect the adequacy and efficiency of movement control in clumsy children.

However, it was not sufficient simply to demonstrate that visuospatial deficits were present in a sample of clumsy children. To determine whether visuospatial deficits are related to motor performance, it is also important to assess a specific visuoperceptual process that is directly related to the motor skill being investigated, in this case, aimed reaching. This study confirmed that clumsy children were impaired in their ability to judge target direction, which is, prima facie, strongly implicated in reaching. It was then possible to investigate the relationship between impaired directional judgements and the mechanisms underlying motor control in aimed reaching.

Although several studies have demonstrated visuospatial deficits in clumsy children, there has been little investigation into the origin of these deficits. Since processing of visuoperceptual information is commonly regarded as a right hemisphere function, impaired right hemisphere functioning in clumsy children would offer a possible explanation for their reduced capacity in visuospatial processing. This study failed to obtain evidence to suggest that processing of visuospatial information was lateralised for either clumsy or control children. However, in simple perceptual tasks children have been observed to show clear evidence of right hemisphere lateralisation (Bryden and Saxby, 1986; Kinsbourne, 1989; Koenig et al., 1990; Rourke et al., 1983). Thus, the failure to find right hemisphere dominance for judgement of target direction, suggests that there were methodological difficulties in the assessment of lateralisation for this task, or the occurrence of type II errors, and these results must be regarded with caution.

Bryden and Saxby (1986) attribute inconsistencies in lateralisation studies to the difficulty in restricting processing to one hemisphere. For example, when assessing lateralisation with a new task, it is often difficult to predict the type of strategies that will be adopted. In this study, children were asked to point to the chosen stimulus, however, many verbalised the number of their choice (they were labelled to assist the tester). Although the task was regarded as primarily visuospatial, it may have had a verbal component and hence the left hemisphere is implicated. Thus, the question of whether right hemisphere processing for visuospatial material is impaired in clumsy children has not been answered using this methodology.

4.3 Deficits in Movement Control

4.3.1 Preprogramming

The integrity of preprogrammed processing in the clumsy children was assessed by analysing movement errors in the initial phase of reaching. The clumsy sample was significantly more variable than the control group in the initial angle of movement direction but, in contrast to measures of variability taken later in the reaching movement, initial variability was independent of available visual information. Since this measure was taken at movement initiation, and given the sensory-motor delay (Carlton, 1981; Elliott, 1993; Jeannerod, 1986; Keele and Posner, 1968), it appears there was insufficient time for corrections to be made. Thus, these findings strongly suggest the presence of preprogramming deficits in the clumsy group. These results are in agreement with other studies suggesting that clumsy children are less accurate than control children in executing movements in the initial or preprogrammed phase of the movement (Forsstrom and von Hofsten, 1982; Schellekens et al., 1983; Smyth, 1991; van der Meulen et al., 1991a and b)

If preprogramming processes are impaired in clumsy children, then the relative differences in the capabilities of the two groups would be expected to continue throughout the movement if the opportunity to rely on corrective control mechanisms was reduced. In the Restricted View (Hand and Target) condition, the clumsy children remained significantly impaired at the end of the reach. In this condition, reaching movements were significantly faster than in the other viewing conditions for both groups, suggesting that subjects spent relatively less time making corrections based on visual and visuokinaesthetic feedback and relatively more time on preprogrammed control. Even though the average movement duration for this condition was greater than 100-200 ms and feedback mechanisms were available, it is possible that subjects chose to preprogram the greater part of the movement because feedback information was unreliable (Jakobson and Goodale, 1991; Smyth 1991, 1994; Zelaznik, 1983). Thus, the impaired performance by the clumsy children in this condition, at both the initial and end stages of reaching, arguably provides further support for the occurrence of preprogramming deficits in this group.

Since the clumsy children were more inaccurate than the control children in judging target direction, it is possible that the high scatter observed for the initial movement direction was a consequence of impaired encoding of target direction at the input stage, rather than a deficit of programming per se. In order to assess the contribution of this visual impairment to the preprogramming deficits observed in the clumsy children, judgement of target direction was used to statistically control for visuoperceptual ability. Unexpectedly, there was no evidence that visuoperceptual ability was an important factor in the accuracy and efficiency of preprogramming. Including visuoperceptual ability as a covariate did not affect the group differences obtained for efficiency of initial aiming accuracy or for end-point performance in the Restricted View (Hand and Target) condition.

The failure of the ANCOVA to eliminate group differences could be dismissed as simply reflecting the lack of a correlation between visual judgements of direction and initial movement accuracy. However, this absence of a correlation, itself implies that visual judgements are not related to performance in the initial stages of reaching. The variance in these samples was sufficient to suggest that the low correlation cannot be explained by low variability. In addition, the low correlation was not due to insensitivity of the perceptual measure since the latter was significantly related to performance in the Full Vision condition suggesting that it was sufficiently sensitive to account for other differences. Thus, it appears that for preprogrammed control, factors over and above judgement of target direction accounted for performance difficulties in reaching.

Of course, it is possible that the inferior performance in preprogramming by the clumsy children reflected visual deficits other than that of processing directional information. Perhaps other visuoperceptual abilities such as judging distance and size contributed to the effect. Nevertheless, prima facie, this result does imply that non-visual factors such as impaired processing of kinaesthetic input or planning problems may have been responsible for poor performance in this condition. Evidence suggests that response preparation is delayed in clumsy children (Bairstow and Laszlo, 1989; Smyth, 1991; van Dellen and Geuze, 1988) and it may be that planning inefficiencies are a primary factor contributing to inaccurate preprogramming in clumsy children. However, the failure to find group differences in reaction time suggests that planning efficiency was not an important factor in this study.

It may be that impaired processing of kinaesthetic input about relative limb positions and muscle tension generated the apparent preprogramming differences between clumsy and control children. Experimental evidence has consistently identified kinaesthetic deficits in clumsy children (Hoare and Larkin, 1991; Laszlo and Bairstow, 1985; Smyth and Glencross, 1986). It is possible that the observed visual deficits in clumsy children are incidental to initial control processes in clumsy children. Further studies using covariate analysis to investigate the relationship between relevant kinaesthetic abilities and movement initiation could clarify the situation.

These results highlight the need to establish a direct, specific relationship between visuoperceptual and motor control processes as a necessary (although not sufficient) condition in exploring relationships between visuoperceptual ability and clumsiness. While van der Meulen et al. (1991a) also identified impaired preprogramming capabilities in clumsy children, these were assumed to reflect an impairment in visual perception of the target position on the basis of earlier reports of visuospatial deficits in clumsy children. However, the present study clearly demonstrates that at movement initiation, other demands apart from the direct processing of visuospatial input are more important.

4.3.2 Visual Feedback

Several studies have argued that if visual feedback mechanisms were impaired in clumsy children they would show more (relative) impairment in full vision conditions than in restricted viewing conditions (Lord and Hulme, 1988; van der Meulen, 1991a and b; Smyth, 1991). In this study, the opposite was observed. The clumsy children showed a relative improvement when full visual information about the moving hand and target was available, compared to performance in the restricted viewing conditions. Thus, despite the presence of deficits in directional judgement, visual feedback mechanisms appeared to improve the reaching performance of the clumsy child.

If the task is not too demanding, continuous relative judgements should allow end-point accuracy to improve, even if utilisation of feedback is inefficient. The negative result here may simply represent a ceiling effect for the control children. Since the clumsy children were more impaired initially, it is perhaps to be expected that they would show a greater improvement in performance. Since visual feedback mechanisms in clumsy children were insufficient to overcome group differences despite the absence of constraints, it is possible that processing of visual feedback is after all impaired in the clumsy group.

Impaired visual feedback processing might be a secondary consequence of deficits in visual perception. To see if this was so, the group differences in the Full Vision condition were analysed using judgement of target direction as a covariate. The results of this analysis suggested that visuoperceptual ability did indeed determine the capacity to make use of visual feedback in the later stage of the movement. It seems that the clumsy children were able to improve performance to some extent by relying on visual feedback corrective mechanisms. However, group differences remained and these were shown to be directly associated with visuoperceptual ability. This suggests that for the clumsy children, the limiting factor to achieving a normal result in the visual feedback condition was the presence of visuoperceptual deficits.

In conclusion, the results suggest that clumsy children are inefficient in their use of visual feedback mechanisms because of visuoperceptual problems but nevertheless rely on visual feedback to correct performance. Since, it has already been shown that clumsy children are also impaired in preprogramming, it is not surprising that they rely on visual feedback corrective mechanisms when this is possible. In full vision conditions, information about the success of the movement is continuously available. Therefore, in the absence of time constraints, it is possible for a clumsy child to make many visual corrections, and finally achieve accuracy.

The present findings clarify questions regarding the integrity of visual feedback mechanisms in clumsy children which were reviewed earlier. The evidence implicating impaired visual feedback processing in clumsy children has been weak but it was postulated that clumsy children might take their inefficiency into account when planning and programming their movements, thus reducing the extent of observable differences. Thus, the failure to find increased group differences in visual feedback compared to non-visual feedback conditions, as obtained here and elsewhere (Lord and Hulme, 1988a; Smyth, 1991; van der Meulen et al., 1991a and b), does not mean that visual feedback mechanisms are intact. The evidence obtained here confirms studies that have observed inferior performance by clumsy children in tasks that are highly dependent on visual feedback (Bairstow and Laszlo, 1989; Lord and Hulme, 1988b; van der Meulen et al., 1991b), and suggests that visual feedback mechanisms in the clumsy children were impaired as a consequence of visuoperceptual deficits. Nevertheless, it seems that despite inefficiencies, the clumsy children were able to use these mechanisms to greatly improve performance.

4.3.3 Visuokinaesthetic feedback

This study also investigated the ability of clumsy children to use visuokinaesthetic feedback to control reaching. In the condition where visual feedback processing was precluded by restricted the view of the moving hand, the two groups differed in their ability to utilise visual information about the target. Consistent with findings for adults (Goodale et al., 1986; Pelisson et al., 1986; Jeannerod, 1986; Prablanc and Martin, 1992; Prablanc et al., 1986), the control children demonstrated a better performance when visual information about target location was available compared to when it was restricted. However, the clumsy children showed no benefit from this additional information. Their performance even appeared to be worse in this condition (although not significantly). It appears that they were unable to correct their reaching movements by comparing visual information about the target position with non-visual information about the position of the moving hand. These results suggest that clumsy children are impaired in their ability to utilise visuokinaesthetic feedback mechanisms.

In movements guided predominantly by visuokinaesthetic feedback control, it is possible that poor visual discrimination would affect the quality of corrective comparisons between the observed target and the felt hand. To assess whether poor visual perception contributed to impaired visuokinaesthetic processing, judgement of target direction was also used as a covariate in the analysis of End Scatter differences in the Restricted View (Hand) condition. Since judgement of target direction was found to be unrelated to differences in this condition, it appears that visuospatial ability does not contribute to effective utilisation of visuokinaesthetic feedback. It may be therefore that poor processing of kinaesthetic information accounts for the reduced capacity to utilise visuokinaesthetic corrective mechanisms. However, kinaesthetic processes were not the explicit focus of this study and further research is required in this area.

4.4 Hemispheric Specialisation in Motor Control

The results of this study support the contention that impaired right hemisphere processing is associated with poor movement control. Although the control children showed no difference in performance across target/hand laterality conditions, the clumsy children were impaired in the predominantly right hemisphere conditions of left hand and left hand/left target. This laterality effect was present regardless of the availability of visual information, which suggests that it was not related to processing of visual information. However, the fact that the hemispheric effect was observed in the later stages of the movement suggests that it may have been related to feedback processes (albeit not visual ones). A lateralisation effect for utilisation of visuokinaesthetic feedback would be consistent with other studies which have found that ability to accurately reproduce finger positions on the basis of kinaesthetic information is greatest with the left hand (Kimura and Vanderwolf, 1970; Roy and MacKenzie, 1978). This interpretation also fits well with the results discussed earlier, which showed that clumsy children appear impaired in their ability to utilise visuokinaesthetic processes to improve their performance.

Alternatively, the errors in the end-point of reaching could be generated by variability due to inefficient programming (van der Meulen et al., 1991a). It has already been demonstrated that clumsy children show deficits in preprogramming, and on the basis of earlier evidence from adults (Guiard et al., 1983), it was expected that impaired right hemisphere processing of motor control would most likely be observed in situations where the movement is predominantly preprogrammed. Since programming is also involved in effecting corrections as well as initiating the movement, and thus is a component of all the viewing conditions, abnormal lateralisation for this process might be expected to be independent of visual conditions. Nevertheless, if the programming component of reaching is lateralised, it is surprising that this effect was not apparent in initial movement errors.

Considered in isolation, it could be argued that impaired performance with the left hand by clumsy children was simply indicative of a practice effect for right hand performance. However, the control children in this study, who presumedly had equal practice with the right hand, did <u>not</u> demonstrate a right hand advantage. This suggests that practice effects alone can not explain the discrepancies in performance for clumsy children. The important point is that the clumsy children showed a relative disadvantage when compared to the control group.

Given the present results and the review of the literature in Chapter 1, it appears that utilisation of visual feedback is unlikely to have been abnormally lateralised in the clumsy sample because the effect was independent of the viewing conditions. It seems likely therefore, that end-point errors in left hand and left target (right hemisphere) conditions reflected abnormal lateralisation for processing of visuokinaesthetic feedback. However, the possibility that preprogrammed control contributed to the observed laterality effects cannot be ruled out and further research is required to further differentiate these effects.

4.5 Methodological Issues

This study introduced two methodological innovations in an attempt to clarify conclusions drawn from other studies investigating reaching movements in clumsy children. Firstly, assessment of visuoperceptual abilities in a task directly related to the investigated movement allowed evaluation of the relationship of visuoperceptual deficits to preprogramming and visual- and visuokinaesthetic-feedback mechanisms. Using statistical controls, it enabled a link between visuoperceptual deficits and visual feedback difficulties to be identified, despite the apparent ability of clumsy children to improve performance through visual feedback guidance. It was also possible to demonstrate that difficulties demonstrated by clumsy children in preprogramming and utilisation of visuokinaesthetic feedback were related primarily to factors other than ability to judge target direction. However, to further our understanding of the relationship between visual perception and movement control, it would be beneficial for future studies to include a more comprehensive assessment of visual perceptual abilities that are relevant to aimed reaching. In particular, the ability of clumsy children to make visual judgements of target size and distance need to be assessed.

This study was primarily intended to evaluate the role of visual information and no direct assessments were made of kinaesthetic abilities. In the Restricted View (Hand) condition, it was assumed that the visuokinaesthetic loop was relied upon to make corrections to the motor program. While poor performance here could result from visual impairment, performance in this condition would also have been particularly sensitive to kinaesthetic abilities. Therefore, the fact that deficiencies in this condition were uncorrelated with the ability to judge target direction might suggest that there were kinaesthetic deficits in this group. This would be consistent with other studies documenting deficits in kinaesthetic processing in samples of clumsy children (Bairstow and Laszlo, 1989; Laszlo, 1990; Laszlo and Bairstow, 1985; Laszlo et al., 1988; Laszlo and Sainsbury, 1993; Smyth, 1994). On the other hand, it is also possible that reduced performance in this condition might reflect planning deficits, or deficiencies in integrating across modalities. To clarify the situation, future studies of aimed reaching also need to assess cross-modal and kinaesthetic abilities in tasks that are directly related to the motor skill being investigated.

The second methodological innovation involved the inclusion of a condition without vision of the target or moving hand. This created less favourable conditions for reliance on visual or visuokinaesthetic feedback mechanisms, by reducing the quality and quantity of perceptual information available during movement execution. This condition could not be regarded as entirely preprogrammed since it was possible for corrections to be made on the basis of the memorised target position. However, the success of this experimental manipulation in changing the extent of reliance on feedback mechanisms is evidenced by the significantly decreased movement times for the Restricted View (Hand and Target) condition. As was also observed by Prablanc and colleagues (1986), the faster movement times also resulted in greater variable error for the control children and most likely reflect uncorrected perceptual input and programming errors. In future research, added instructions emphasising speed of execution in this task may further reduce opportunities to utilise sensory feedback and encourage the execution of predominantly preprogrammed movements.

While group differences were found for all measures of movement variability (Initial Scatter, Halfway Scatter and End Scatter), this study found no changes in

Mean Error or Initial Error. However, differences in these measures would not normally be expected since it would suggest that clumsy children make initial and end-point errors in a systematic fashion. It is more likely the case that clumsy children are unable to execute movements as they would like, which results in reaching movements that follow variable paths either side of the intended trajectory. Thus, measures of movement variability are regarded as more valid measures of movement accuracy.

Group differences in Movement Time and Reaction Time were also not observed. In an environment where speed of execution has not been constrained, subjects can make their own decisions about speed/accuracy trade-offs. In this experiment, it appears that environmental manipulations resulted in both groups making similar decisions. For example, both groups moved more quickly in the Restricted View (Hand and Target) condition. Thus, as was obtained in this study, if movement and reaction times are similar, we can expect to see the differences in ability reflected in accuracy measures.

The observation that the clumsy children were impaired under all conditions also raises the possibility that poor motor control may simply represent a deficiency in executive mechanisms. However, visual judgement of target direction was found to account for the differences between clumsy and control groups in the Full Vision condition which suggests that deficiencies at the execution stage do not explain differences in utilisation of visual feedback. On the other hand, it is still possible that impairment in the preprogrammed component of the movement reflected deficiencies in execution, since in this study, the initial errors made by the clumsy group were not related to visuoperceptual deficits. Demonstration of a relationship between errors in movement initiation and kinaesthetic, planning or programming disabilities could clarify the extent to which executive processing contributes to clumsiness in these children. It may also be that deficiencies in executive mechanisms are more evident in some types of movement than in others. For example, errors in execution may be greater in motor tasks requiring larger and faster movements than those examined here.

The assessment of visuoperceptual abilities showed no evidence of hemispheric specialisation in either group despite a large body of literature suggesting that a right hemisphere effect could be expected in young children. Moreover, for motor performance, it was not clear whether the target/hand laterality deficits related to visuokinaesthetic or preprogrammed processes. Future research needs to assess hemispheric specialisation for both visuospatial and kinaesthetic capabilities while ensuring that verbal strategies are excluded from the response strategy.

It could be that difficulties in obtaining consistent results concerning lateralisation in clumsy children reflect the heterogeneity of the group being studied. Historically, clumsiness in children has been attributed to deficits of praxis (a predominantly left hemisphere function), or deficits in visuospatial recognition (a right hemisphere function) (Walton et al., 1962). It may be useful for future research to attempt to classify clumsy children into relevant sub-types according to the function of the left and right cerebral hemispheres. While the experimental assessment of processes of motor control goes some way towards identifying and delineating common deficits in clumsy children, a neuropsychological approach could assist in the categorisation of relevant sub-types. For example, neuropsychological testing might asses the integrity of frontal/executive and posterior/parietal systems, as well as left and right hemisphere function. Neuropsychological profiles could then be combined with experimental results to provide a unifying functional description of deficits in clumsy children which would provide valuable information for treatment purposes.

4.6 Conclusion

The major aim of this study was to confirm the existence of visuoperceptual deficits in clumsy children and determine whether these deficits affected performance in underlying processes of visuomotor control. The results clearly identified the presence of visuoperceptual deficits (directional judgement). Clumsy children were also shown to be more inefficient in the utilisation of the three main mechanisms investigated: preprogramming, visuokinaesthetic feedback and visual feedback control. Thus, clumsy children made more errors in movement initiation, the clumsy children were unable to correct their reaching movements on the basis of visuokinaesthetic information and visual feedback mechanisms in clumsy children were insufficient to overcome group differences despite the absence of constraints.

Investigation of the relationship between visuoperceptual ability and visual feedback mechanisms showed that the errors made by clumsy children in visual judgements of target direction, were related entirely to their deficiencies in visual feedback control. Nevertheless, despite these deficiencies, the clumsy children utilised visual feedback to improve the accuracy of their reaching.

In contrast, impaired preprogramming in clumsy children, as measured by initial error variability, was not found to be related to visuoperceptual input. In addition, utilisation of visuokinaesthetic processes were also found to be unrelated to visuoperceptual deficits in clumsy children. This study has demonstrated that for preprogramming and visuokinaesthetic feedback control, other factors apart from processing of visuospatial information are important. To fully assess preprogramming and visuokinaesthetic feedback mechanisms, future research must also assess kinaesthetic and planning capabilities in tasks relevant to aimed reaching.

The second aim was to investigate whether clumsy children showed impaired right hemisphere processing for visual perception and movement control. Assessment of visuospatial capabilities failed to reveal lateralisation effects for either clumsy or control children and it was concluded that improvements in assessment methodology are required before it can be established whether clumsy children show impaired right hemisphere processing for visual perception. However, clumsy children did demonstrate impaired right hemisphere processing for reaching movements, independently of the amount of visual information available. On the basis of these results it was suggested that hemispheric specialisation for utilisation of visuokinaesthetic feedback and/or preprogramming of the movement may be abnormal in clumsy children.

In this study, clumsy children have been shown to be impaired in visuospatial perception, utilisation of visuokinaesthetic feedback and in preprogramming capabilities. These three skills have all been identified as being specialised for the right hemisphere. Moreover, evidence was obtained suggesting that movements performed under right hemisphere control by clumsy children are significantly inferior to control children. While not conclusive, it is possible that the occurrence of these deficits in clumsy children are due to a general deficit in right hemisphere processing. Further research is needed to adequately evaluate lateralisation of visuospatial, kinaesthetic and motor skills in clumsy children.

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Appendix A

Means and SDs for measures of reaching performance under Viewing and Target/Hand Laterality conditions

Variables (n=16 in each cell)	Rt hand/ Lt target	Rt hand/ Rt target	Lt hand/ Lt target	Lt hand/ Rt target
Reaction Time (msec)				
Restricted View (H/Tg)				
Control	464 (110)	494 (143)	463 (126)	444 (106)
Clumsy	459 (120)	458 (127)	449 (124)	428 (110)
Restricted View (Hand)				
Control	490 (109)	533 (104)	510 (96)	473 (119)
Clumsy	458 (142)	497 (127)	474 (142)	431 (100)
Full Vision				
Control	484 (155)	543 (178)	505 (121)	473 (134)
Clumsy	434 (71)	447 (127)	446 (121)	440 (134)
Movement Time (msec)				
Restricted View (H/Tg)				
Control	759 (269)	752 (298)	722 (304)	836 (264)
Clumsy	659 (290)	606 (356)	616 (361)	635 (283)
Restricted View (Hand)				
Control	898 (338)	796 (298)	761 (246)	900 (276)
Clumsy	793 (315)	728 (385)	659 (244)	817 (297)
Full Vision				
Control	913 (312)	853 (269)	840 (276)	903 (265)
Clumsy	813 (258)	748 (268)	761 (249)	803 (251)
Mean Error (cm)				
Restricted View (H/Tg)				
Control	2.91 (1.29)	2.06 (1.29)	2.77 (1.46)	2.76 (1.24)
Clumsy	2.46 (1.26)	2.40 (1.31)	2.03 (1.03)	2.42 (1.36)
Restricted View (Hand)				
Control	2.79 (1.11)	2.10 (1.48)	2.50 (0.95)	3.58 (1.45)
Clumsy	2.21 (1.32)	2.05 (1.31)	2.54 (1.74)	2.95 (1.68)
Full Vision				
Control	1.31 (0.67)	0.60 (0.46)	1.16 (0.58)	0.79 (0.39)
Clumsy	1.17 (0.68)	0.93 (0.74)	1.15 (0.51)	1.12 (0.77)

Initial Error (deg)				
Restricted View (H/Tg)				
Control	10.01 (6.18)	5.68 (3.55)	5.28 (4.74)	10.95 (4.09)
Clumsy	9.15 (6.18)	6.61 (4.06)	4.75 (4.19)	13.28 (4.70)
Restricted View (Hand)				
Control	10.60 (5.42)	6.11 (3.74)	5.11 (4.75)	12.22 (4.98)
Clumsy	12.10 (4.52)	5.29 (3.82)	9.29 (7.68)	13.86 (5.08)
Full Vision				
Control	9.25 (5.10)	5.96 (3.12)	5.91 (4.69)	11.64 (3.79)
Clumsy	12.74 (4.91)	6.49 (4.31)	6.19 (4.10)	13.27 (5.08)
Initial Scatter (deg)				
Restricted View (H/Tg)				
Control	5.48 (2.72)	4.07 (1.59)	5.15 (2.01)	5.76 (2.93)
Clumsy	6.95 (2.94)	7.07 (2.82)	7.29 (4.94)	6.75 (2.34)
Restricted View (Hand)				
Control	4.90 (2.62)	4.14 (1.85)	4.92 (2.68)	5.58 (3.19)
Clumsy	8.10 (4.02)	5.17 (2.57)	8.37 (8.37)	7.14 (4.20)
Full Vision				
Control	5.16 (2.36)	4.75 (2.41)	5.77 (3.11)	5.47 (3.63)
Clumsy	7.77 (7.87)	7.02 (4.38)	8.57 (7.84)	5.92 (2.80)
Half Way Scatter (cm)				
Restricted View (H/Tg)				
Control	1.38 (0.41)	1.21 (0.30)	1.08 (0.33)	1.29 (0.40)
Clumsy	1.42 (0.75)	1.77 (0.85)	1.69 (0.80)	1.78 (0.66)
Restricted View (Hand)				
Control	1.06 (0.31)	1.01 (0.31)	1.09 (0.29)	1.23 (0.39)
Clumsy	1.77 (0.68)	1.55 (0.80)	1.57 (0.87)	1.89 (1.31)
Full Vision				
Control	0.99 (0.34)	0.92 (0.31)	1.04 (0.50)	1.09 (0.61)
Clumsy	1.49 (0.87)	1.34 (0.61)	1.66 (1.02)	1.56 (0.82)
End Scatter (cm)				
Restricted View (H/Tg)				
Control	1.65 (0.36)	1.62 (0.59)	1.46 (0.57)	1.62 (0.60)
Clumsy	1.84 (0.73)	1.71 (0.70)	1.98 (0.94)	2.21 (0.82)
Restricted View (Hand)				
Control	1.28 (0.31)	1.37 (0.35)	1.45 (0.53)	1.53 (0.45)
Clumsy	2.09 (0.53)	1.75 (0.58)	2.63 (1.77)	1.93 (0.75)
Full Vision				
Control	0.67 (0.20)	0.55 (0.23)	0.54 (0.16)	0.75 (0.31)
Clumsy	0.80 (0.28)	0.72 (0.32)	0.73 (0.29)	0.87 (0.32)

Appendix B

Repeated measures analysis of variance for measures of reaching performance: Group (2) x Viewing Condition (3) x Target/Hand Laterality (4)

Source of Variance	SS	df	MS	F	sig
Reaction Time					
Group	0.14	1,30	0.14	1.33	0.26
Viewing	0.04	2,60	0.02	1.46	0.24
Group x Viewing	0.03	2,60	0.02	1.04	0.36
Laterality	0.11	3,77	0.04	5.37	0.002**a
Group x Laterality	0.01	3,90	0.00	0.50	0.680
Viewing x Laterality	0.01	6,180	0.00	0.45	0.844
Group x View. x Lat.	0.01	6,180	0.00	0.39	0.882
Movement Time					
Group	1.09	1,30	1.09	1.43	0.241
Viewing	1.21	2,54	0.60	8.32	0.000**a
Group x Viewing	0.05	2,60	0.02	0.33	0.718
Laterality	0.57	3,79	0.19	12.44	0.000**a
Group x Laterality	0.02	3,90	0.01	0.36	0.784
Viewing x Laterality	0.12	6,180	0.02	1.69	0.126
Group x View. x Lat.	0.05	6,180	0.01	0.64	0.695
Mean Error					
Group	2.41	1,30	2.41	0.82	0.373
Viewing	194.25	2,60	97.13	60.56	0.000**
Group x Viewing	3.95	2,60	1.97	1.23	0.299
Laterality	17.71	3,90	5.90	3.37	0.022*
Group x Laterality	2.88	3,90	1.59	0.91	0.441
Viewing x Laterality	14.07	6,180	2.34	3.10	0.007**
Group x View. x Lat.	4.63	6,180	0.77	1.02	0.414

a- Huynh-Feldt Epsilon used to adjust df for averaged results

Source of Variance	SS	df	MS	F	sig
Initial Error					
Group	136.26	1,30	136.26	1.92	0.176
Viewing	81.07	2,60	40.53	2.46	0.094
Group x Viewing	25.53	2,60	12.76	0.77	0.466
Laterality	3112.68	3,90	1037.56	32.29	0.000**
Group x Laterality	34.92	3,90	11.64	0.36	0.780
Viewing. x Laterality	70.36	6,180	11.73	0.93	0.477
Group x View. x Lat.	167.74	6,180	27.96	2.21	0.044*
Initial Scatter					
Group	415.65	1,30	415.65	13.34	0.001**
Viewing	5.41	2,60	2.71	0.21	0.809
Group x Viewing	2.87	2,60	1.43	0.11	0.894
Laterality	91.22	3,90	30.41	1.51	0.219
Group x Laterality	43.11	3,90	14.37	0.71	0.548
Viewing x Laterality	44.75	6,180	7.46	0.57	0.755
Group x View. x Lat.	37.16	6,180	6.19	0.47	0.828
Half Way Scatter					
Group	24.81	1,30	24.81	14.23	0.001**
Viewing	2.48	2,60	1.24	3.37	0.041*
Group x Viewing	0.48	2,60	0.24	0.65	0.528
Laterality	1.57	3,90	0.52	2.02	0.117
Group x Laterality	0.32	3,90	0.11	0.41	0.746
Viewing x Laterality	1.34	6,180	0.22	0.66	0.684
Group x Viewing	1.76	6,180	0.29	0.87	0.519
End Scatter					
Group	15.11	1,30	15.11	16.57	0.000**
Viewing	94.44	2,60	47.22	137.47	0.000**
Group x Viewing	4.83	2,60	2.41	7.02	0.002**
Laterality	2.29	3,90	0.76	3.06	0.032*
Group x Laterality	2.14	3,90	0.71	2.85	0.042*
Viewing. x Laterality	3.50	6,180	0.58	1.51	0.177
Group x View. x Lat.	2.76	6,180	0.46	1.19	0.314

Appendix C

ANCOVA with Number of Visual Errors as covariate

Means for Initial, Halfway and End Scatter adjusted for the covariate (Number of Visual Errors)

	Clumsy	Normal	F	p
Initial Scatter	7.01	5.26	9.59	0.004
Half Way Scatter	1.58	1.16	10.28	0.003
End Scatter				
Restricted View(H/Tg)	1.93	1.60	4.46	0.043
Restricted View(Hand)	2.09	1.41	17.33	0.000
Full Vision	0.76	0.65	2.76	0.107ns